

AD \_\_\_\_\_

Award Number: W81XWH-10-1-0578

TITLE: Neural Mechanisms Linking Mild Traumatic Brain Injury and Anxiety States in an Animal Model

PRINCIPAL INVESTIGATOR: Gina Forster, Ph.D.

CONTRACTING ORGANIZATION: The University of South Dakota  
Vermillion, SD, 57069

REPORT DATE: September 2011

TYPE OF REPORT: Annual

PREPARED FOR: U.S. Army Medical Research and Materiel Command  
Fort Detrick, Maryland 21702-5012

DISTRIBUTION STATEMENT: Approved for Public Release;  
Distribution Unlimited

The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision unless so designated by other documentation.

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.					
1. REPORT DATE September 2011		2. REPORT TYPE Annual		3. DATES COVERED 1 September 2010 – 31 August 2011	
4. TITLE AND SUBTITLE  Neural Mechanisms Linking Mild Traumatic Brain Injury and Anxiety States in an Animal Model				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER W81XWH-10-1-0578	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)  Gina Forster, Ph.D.; Michael Watt, Ph.D.; Pat Manzerra, Ph.D.  E-Mail: gforster@usd.edu				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)  The University of South Dakota Vermillion, SD 57069				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Medical Research and Materiel Command Fort Detrick, Maryland 21702-5012				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for Public Release; Distribution Unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT  Previous correlational studies suggest that mild traumatic brain injury (TBI) is associated with an increase in the prevalence of anxiety disorders, including posttraumatic stress disorder (PTSD). By using a relevant animal model, this research demonstrates that mild TBI can result in increased fear learning and anxiety states that mimic the symptoms of generalized anxiety disorder and PTSD. Furthermore, this research suggests that heightened fear and anxiety states following mild TBI may result from alterations to cell death and neuronal number in limbic brain regions such as the hippocampus and amygdala. Recent data generated from this project also suggests that experiencing psychosocial stress concurrent with mild brain injury exacerbates subsequent anxiety states. Overall, the current rodent model of mild TBI appears to be a useful model to explore the neurobiological link between mild TBI and anxiety states, and future research will be directed at determining the neurochemical mechanisms by which mild TBI and psychosocial stress interact to exacerbate anxiety states. This will allow better understanding of the consequences of war injuries like mild TBI, and how such injury could be treated to prevent long-term disability.					
15. SUBJECT TERMS Mild traumatic brain injury; Posttraumatic stress disorder; Neurobiology of anxiety disorders.					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			USAMRMC
U	U	U	UU	45	19b. TELEPHONE NUMBER (include area code)

## Table of Contents

	<u>Page</u>
Introduction.....	4
Body.....	4
Key Research Accomplishments.....	8.
Reportable Outcomes.....	8
Conclusion.....	9
References.....	9
Appendix.....	10

## Introduction:

The greater incidence of mild traumatic brain injury (TBI) arising from recent military conflicts could be in part responsible for the increasing occurrence of posttraumatic stress disorder (PTSD) in US troops (Kennedy et al., 2007; Gaylord et al., 2008; Hoge et al., 2008). Brain regions susceptible to shearing and bruising during a mild TBI incident overlap with those brain regions that process emotion and regulate behavioral and physiological responses to stressors (Kennedy et al., 2007; Bryant, 2008). These convergent brain areas include the medial prefrontal cortex (mPFC) and the temporal lobe including the amygdala and hippocampus (Kennedy et al., 2007; Bryant, 2008). Alterations to serotonergic function have been implicated in anxiety disorders including PTSD (Stam, 2007; Lowry et al., 2008). Serotonergic activity in the amygdala is related to the onset while serotonin release in the mPFC is related to the cessation of fear behavior in an animal model (Forster et al., 2006). Thus, amygdala hyperfunction/mPFC hypofunction observed in PTSD (Milad et al., 2006; Rauch et al., 2006; Stam, 2007) may be a result of altered serotonin activity, which could arise from mild trauma to these regions. Furthermore, serotonin activity in relation to fear and anxiety states is regulated by corticotrophin-releasing factor (CRF), released in response to physical and psychological stressors (Forster et al., 2006; Lukkes et al., 2009a). Severe or chronic stressors increase CRF levels and the levels of CRF receptors, thus affecting regulation of serotonin activity and leading to heightened anxiety states (as reviewed by Stam, 2007; Lukkes et al., 2009a). Therefore, both CRF and serotonin represent important potential targets for the treatment of PTSD (Stam, 2007), but the impact of mild TBI on these systems is unknown. Therefore current research addresses the following Objectives:

- Objective 1: Establish whether mild TBI results in neural death or altered serotonin/CRF function within limbic brain regions that are implicated in the symptomology of posttraumatic stress disorder (PTSD).
- Objective 2: Relate altered function of limbic brain regions following mild TBI with psychobehavioral and neuroendocrine symptoms of PTSD.

## Body:

The Milestones within the approved Statement of Work for this award are outlined in Table 1 below.

*Table 1: Project Objectives and Approved Milestones*

	Quarter 1 Year 1	Quarter 2 Year 1	Quarter 3 Year 1	Quarter 4 Year 1	Quarter 1 Year 2	Quarter 2 Year 2
<b>Objective 1:</b> Establish whether mild TBI results in neural death or altered neural/neurochemical function within limbic brain regions that are implicated in the symptomology of PTSD.						
<b>Task 1:</b> Animal IACUC approved	University of South Dakota					
<b>Task 2:</b> Measure markers of neuronal death susceptibility, neuronal number and apoptotic neurons.	Begin to collect samples end of this quarter.	Collect samples and begin analysis.	Analyze samples.			
<b>Task 3:</b> Measure serotonin.			Collect Samples	Analyze samples.		
<b>Task 4:</b> Measure CRF and receptors.				Samples Collected.	Analyze samples.	
<b>Task 5:</b> Initial Dissemination of Results			Conference Presentation			
<b>Objective 2:</b> Relate altered function of limbic brain regions following mild TBI with psychobehavioral and neuroendocrine symptoms of PTSD.						
<b>Task 1:</b> Fear conditioning and extinction testing				Begin behavioral testing.	Continue behavioral testing.	Finish behavioral testing beginning of this quarter. Data Analyzed.
<b>Task 2:</b> Dissemination of Results				Write manuscripts on molecular data.	Write manuscripts on neurochemical data.	Write manuscripts on behavioral data. Conference presentation.

The following reports on progress made towards the Objectives and Tasks within Year 1 (Table 1).

*Objective 1 Task 1 - Obtain IACUC approval from the University of South Dakota to perform the research.*  
IACUC approval from the University of South Dakota, and approval from the USAMRMC Animal Care and Use Research Office were both obtained prior to the award starting. This allowed research to begin immediately upon receiving the award on 9/1/10.

*Objective 1 Task 2 – Collect and analyze samples related to neuronal number, neuronal death and apoptosis following mild TBI.*

The investigators collected neural tissue from young adult male rats that were subjected to weight drop (mild TBI) either 4 days or 9 days following the mTBI procedure (please see Meyers et al manuscript in the Appendix for detailed methods). There was no gross morphological damage incurred as a result of the mild TBI. Also, tests of motor function were conducted prior to tissue collection to ensure that the weight drop did not produce a motor deficit that would indicate a more moderate to severe injury (please see Figure 7 of Meyers et al manuscript in the Appendix). Brains were sectioned and stained to identify neurons for neuronal cell counts, and also stained using the TUNEL method to identify apoptotic cells. Regions of the limbic system thought to mediate anxiety states were analyzed using stereological methods (please see Meyers et al manuscript in the Appendix for detailed methods). These included the medial prefrontal cortex, amygdala subregions (medial, central and lateral), and dorsal and ventral subregions of the hippocampus (CA1, CA3 and dentate gyrus). Statistical analysis of the neuronal cell counts suggested selective neuronal loss in the CA1 region of the dorsal hippocampus, and increased cell number in the medial and lateral subregions of the amygdala 9 days following mild TBI (please see Table 3 and Figures 1 & 2 of the Meyers et al manuscript in the Appendix). These alterations to cell numbers appear to be due to changes in apoptosis in these regions. For example, significantly increased density of apoptotic cells in the CA1 region of the dorsal hippocampus was observed 4 days following mild TBI (Figure 4 of Meyers et al manuscript in the Appendix), suggesting that the decreased neuronal number observed in this region at 9 days following mild TBI was due to increased programmed cell death following the injury. On the other hand, significantly decreased density of apoptotic cells was observed in the medial and lateral subregions of the amygdala 4 and 9 days following mild TBI (Figure 3 of Meyers et al manuscript in the Appendix), suggesting that increased neuronal numbers in these regions at 9 days following mild TBI were due to decreased programmed cell death as a result of mild TBI. Overall, these findings imply that mild TBI differentially activates pro-apoptotic mechanisms in the hippocampus and pro-survival molecular pathways in the amygdala, which should be tested by future research (please see the Discussion of the Meyers et al manuscript in the Appendix for a detailed discussion of this point).

Decreased neurons in the dorsal CA1 region suggested that mild TBI may alter contextual fear conditioning (Hunsaker and Kesner, 2008) while increased amygdala neuronal counts may predict increased fear conditioning and generalized anxiety states (Goosens and Maren, 2001; Rauch et al., 2006). To test the functional consequences of the neuronal changes observed, rats were subjected to control or mild TBI procedures and were tested either for contextual fear conditioning and extinction or for generalized anxiety behavior (please see Meyers et al manuscript in the Appendix for methods details). As predicted by the neural changes seen following mild TBI, rats subjected to mild TBI showed heightened contextual fear conditioning (Figure 5 of Meyers et al manuscript in the Appendix) that could not be explained by heightened nociception (Figure 5C of Meyers et al manuscript in the Appendix). Furthermore, rats subjected to mild TBI also showed increased generalized anxiety-like behaviors (Figure 6 of Meyers et al manuscript in the Appendix). Together, these data suggest discrete changes in neural numbers in the limbic system following mild TBI, which are reflected by heightened conditioned fear and anxiety states. Overall, this animal model appears to represent a good tool to assess the neurobiological link between mild TBI and anxiety states.

*Objective 1 Task 3 – Collect and analyze samples to measure serotonin levels in the limbic system of rats exposed to mild TBI with or without psychosocial stress.*

The collection of brain tissue for this objective has been completed with brains obtained seven days following one of four treatments (n = 10-12 per treatment group): 1) control handling and control surgery 2) control handling and mild TBI surgery 3) social defeat stress and control surgery and 4) social defeat stress and mild TBI surgery. Social defeat stress was used as the psychosocial stressor in these experiments and was performed

immediately prior to the mild TBI or sham surgery, using procedures established in the laboratory of the Co-investigator, Dr. Watt (e.g. Watt et al., 2009). All of the brains from these rats have been sectioned to allow microdissection of the regions of interest and serotonin measures (via HPLC) to be conducted. The dorsal raphe nucleus (source of serotonin neurons) has been dissected and samples analyzed with HPLC and electrochemical detection (Watt et al., 2009). Since our HPLC system also detects other related monoamines that are implicated in anxiety disorders (such as norepinephrine, epinephrine and dopamine) within the same sample as serotonin (Watt et al., 2009), we also analyzed the levels of these monoamines in the dorsal raphe nucleus. Following HPLC analysis of the supernatant drawn from the dissected tissue, the tissue content of each sample was analyzed using a Bradford assay, such that the level of monoamine in each sample (pg) was normalized against the amount of tissue in each sample ( $\mu\text{g}$ ) to provide a  $\text{pg}/\mu\text{g}$  value for each sample (Watt et al., 2009 and Fig 1 below). The medial prefrontal cortex, dorsal and ventral hippocampus and have been dissected and are stored in buffer at  $-80^{\circ}\text{C}$  until they can be injected into the HPLC system for electrochemical detection of serotonin, and we are currently dissecting the amygdala regions. While the projected milestones (Table 1) suggested we could be finished with the analysis of these samples by the fourth quarter of Year 1, this was not the case. This was because the pump that disperses mobile phase and sample throughout the HPLC system started to leak after running the raphe samples and was eventually beyond repair. This is quite a specialized pump, and it took several weeks to find a colleague who could lend us a replacement pump to fit to our system. We have the system running again, and are in the final processes of conducted a variety of validation checks, and will be able to continue to analyze the samples waiting in the freezer by early October of 2011.

Of the samples we were able to analyze for serotonin and other monoamines, we found that neither mild TBI, social defeat stress, nor the combination of the two affected serotonin levels in the dorsal raphe nucleus (Table 2). However, both mild TBI or social defeat stress alone significantly reduced epinephrine levels in the dorsal raphe nucleus, although the combined mild TBI and social defeat stressor did not further impact epinephrine levels in this region (Fig 1). These findings suggest that epinephrine neurotransmission in the dorsal raphe may be impaired following either brain injury or stress. Since receptors for epinephrine can alter the activity of serotonin neurons in the dorsal raphe nucleus (Judge and Gartside, 2006), these findings predict that serotonin activity in terminal regions such as the hippocampus, prefrontal cortex and amygdala will be affected by mild TBI and/or psychosocial stress. This will be tested with the analysis of samples from these regions, as discussed above. The interesting implication of the finding from the dorsal raphe is that mild traumatic brain injury results in the same changes in the neurochemistry of this brain region as psychosocial stress experience.



*Figure 1: Epinephrine levels in the dorsal raphe nucleus following mild TBI and/or psychosocial stress (social defeat), 7 days following injury. Bars with different letters are significantly different from one another ( $P < 0.05$ ).  $n = 10-12$  per group.*

*Table 2: Mean monoamine levels ( $\text{pg}/\mu\text{g}$ ) in the dorsal raphe nucleus following mild TBI and/or psychosocial stress (social defeat), 7 days following injury ( $n = 10-12$  per group)*

Monoamine	Control	mTBI	Defeat	mTBI & Defeat	P Value
Norepinephrine	37.46	32.53	31.17	30.45	0.146
Dopamine	03.48	02.97	03.16	02.89	0.180
Serotonin	32.94	29.19	31.84	29.38	0.307

Objective 1 Task 4 – Collect samples to measure CRF receptor levels in the limbic system of rats exposed to mild TBI with or without psychosocial stress.

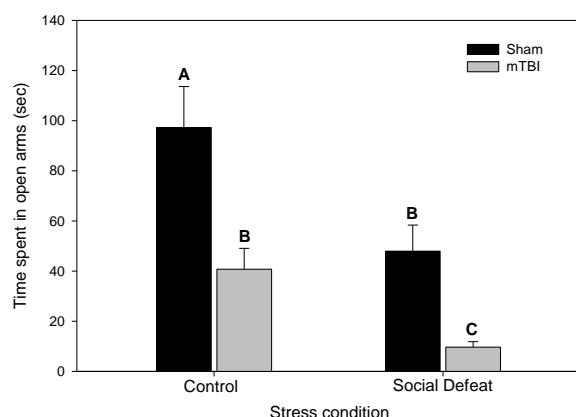
The collection of brain tissue for this objective was completed in the 4<sup>th</sup> quarter of Year 1, with brains obtained following one of four treatments (n = 10 per treatment group): 1) control handling and control surgery 2) control handling and mild TBI surgery 3) social defeat stress and control surgery and 4) social defeat stress and mild TBI surgery. All of the brains from these rats have been sectioned to allow microdissection of the regions of interest and measures of CRF receptors in the serotonergic regions outlined in Task 3 above, using methods established in the PI's laboratory (Lukkes et al., 2009b). This analysis will be conducted in the first quarter of Year 2 (see Table 1).

Objective 1 Task 5: - Initial dissemination of results via presentation at a scientific conference.

The investigators (Forster, Watt and Meyer) attended the annual Society for Neuroscience meeting (San Diego, November 13-17<sup>th</sup>, 2010). Our research findings (particularly those from Objective 1 Task 2) were presented by Dr. Forster and Ms. Meyer in the “Animal Models of Traumatic Brain Injury” session of this meeting. The presentation was titled: Meyer, D.L., Davis, D., Barr, J.L., Manzerra, P., and Forster, G.L. (2010). Neuronal loss within the limbic system in a rat model of closed mild traumatic brain injury. *Society for Neuroscience Abstracts*, 467.17. This data was eventually written as a manuscript and submitted to the journal *Experimental Neurology* in July of 2010 (please see the Meyers et al manuscript included in the Appendix). This manuscript is still currently in review.

Objective 2 Task 1: - Relate altered function of limbic brain regions following mild TBI with fear/anxiety behaviors.

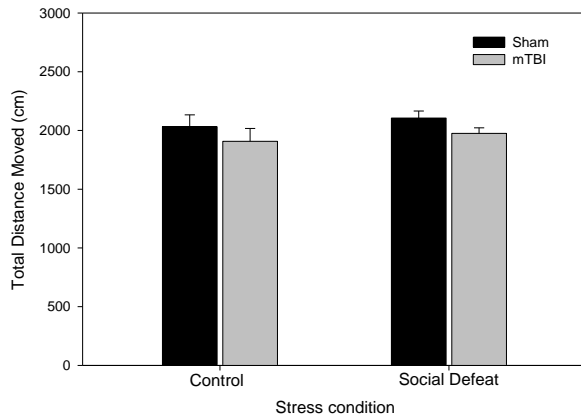
As described for Objective 1 Task 2, mild TBI resulted in increased anxiety states and fear conditioning (please see Figure 5 of the Meyers et al manuscript in the Appendix). We plan to extend these finding within Objective 2 by determining whether psychosocial stress (social defeat) further impacts anxiety states and fear conditioning. As indicated by the milestones in Table 1, we started to collect behavioral data for Objective 2. Rats were randomly assigned to one of four groups, treatments: 1) control handling and control surgery 2) control handling and mild TBI surgery 3) social defeat stress and control surgery and 4) social defeat stress and mild TBI surgery. They were then either tested for anxiety behavior or fear conditioning 7 days following treatment. Five rats per group have been tested in the fear conditioning paradigm, and five more per group will be tested in the first and second quarters of Year 2 as outlined by Table 1 (please see the Meyers et al manuscript in the Appendix for detailed methods). The freezing response to footshock on day 1, and to the environment on the subsequent days will be scored from the video footage obtained from these experiments, with the expectation that mild TBI with psychosocial stressor will result in greater fear conditioning (greater freezing to the environment) and poorer extinction of this response.



*Figure 2: Time spent in open arms of the elevated plus maze 7 days following mild TBI and/or psychosocial stress (social defeat). Bars with different letters are significantly different from one another ( $P < 0.05$ ). n = 10 per group.*

Ten rats per group have been tested for generalized anxiety behavior using the elevated plus maze (please see the Meyers et al manuscript in the Appendix for detailed methods). We found that both mild TBI

and social defeat on their own significantly reduced time spent on open arms of the maze, indicative of greater anxiety states (Fig 2). Interestingly, the combination of mild TBI and psychosocial stressor further increased anxiety states (Fig 2). Neither treatment affected general activity in the maze (Fig 3) suggesting that the reduced time spent in open arms of the maze was not simply due to a motor deficit. Overall, these findings suggest that that behaviorally, mild TBI procedures a very similar anxiogenic profile as psychosocial stress, and that the combination of mild TBI with a psychosocial stressor (such as being the recipient of aggression) results in greater psychological effects than either alone. These behavioral findings will be related to the neurochemical findings from Objective 1 when they become available.



*Figure 3: Total distance moved in the elevated plus maze 7 days following mild TBI and/or psychosocial stress (social defeat). No significant differences between groups ( $P > 0.05$ ).  $n = 10$  per group.*

#### Objective 2 Task 2: - Dissemination of results by writing and submitting manuscripts for publication.

We submitted the first set of results for publication to the journal *Experimental Neurology* in July of 2011. Please see the Meyers et al manuscript included in the Appendix. This manuscript is currently still under review by the journal.

#### **Key Research Accomplishments:**

- Mild TBI in a young adult male rat model results in increased fear learning and anxiety states when measured within 2 weeks of the injury.
- Mild TBI also results in alterations to programmed cell death and neuronal numbers in regions of the limbic system that mediate fear and anxiety.
- Alterations to neuronal number following mild TBI do not become apparent until between 5-9 days following the injury.
- Experiencing psychosocial stress concurrent with mild TBI exacerbates anxiety states when compared to mild TBI alone or psychosocial stress alone.

#### **Reportable Outcomes:**

This research has resulted in the following outcomes:

- A scientific presentation at the 2010 Annual Society for Neuroscience Meeting (San Diego, November 13-17<sup>th</sup>, 2010): Meyer, D.L., Davis, D., Barr, J.L., Manzerra, P., and Forster, G.L. (2010). Neuronal loss within the limbic system in a rat model of closed mild traumatic brain injury. *Society for Neuroscience Abstracts*, 467.17.
- A manuscript submitted to *Experimental Neurology* for peer-review: Meyer, D.L., Davis, D.R., Barr, J.L., Manzerra, P., and Forster, G.L. Mild Traumatic Brain Injury in the Rat Alters Neuronal Number in the Limbic System and Increases Conditioned Fear and Anxiety-like Behaviors. *Experimental Neurology*, in review.
- A scientific abstract submitted (and accepted) for presentation at the Faculty for Undergraduate Poster Session at the 2011 Society for Neuroscience Meeting (Washington D.C., November 12-16<sup>th</sup>, 2011) by



an undergraduate student working on this project as a component of their research training: Davis, D.R., Meyer, D.L., Barr, J.L., Manzerra, P., and Forster, G.L. (2011). Increased Anxiety States and Contextual Fear Conditioning in Closed Traumatic Brain Injury Mirroring Post-Traumatic Stress Disorder. *FUN Poster Session*, accepted abstract.

- Ms. Danielle Meyers received training and experience on this project that directly assisted her successful application to Nursing School at the South Dakota State University (SDSU). She is currently in the first year of the fast-track nursing program at SDSU.

## Conclusions:

Previous correlational studies suggest that mild TBI is associated with an increase in the prevalence of anxiety disorders, including PTSD. By using a relevant animal model, this research demonstrates that mild TBI can result in increased fear learning and anxiety states that mimic the symptoms of generalized anxiety disorder and PTSD. Furthermore, this research suggests that heightened fear and anxiety states following mild TBI may result from alterations to cell death and neuronal number in limbic brain regions such as the hippocampus and amygdala. Recent data generated from this project also suggests that experiencing psychosocial stress concurrent with mild brain injury exacerbates subsequent anxiety states. Overall, the current rodent model of mild TBI appears to be a useful model to explore the neurobiological link between mild TBI and anxiety states, and future research will be directed at determining the neurochemical mechanisms by which mild TBI and psychosocial stress interact to exacerbate anxiety states. This will allow better understanding of the consequences of war injuries like mild TBI, and how such injury could be treated to prevent long-term disability.

## References:

- Bryant, R. A. (2008). Disentangling mild traumatic brain injury and stress reactions. *N Engl J Med*, 358(5), 525-527.
- Forster, G. L., Feng, N., Watt, M. J., Korzan, W. J., Mouw, N. J., Summers, C. H., & Renner, K. J. (2006). Corticotropin-releasing factor in the dorsal raphe elicits temporally distinct serotonergic responses in the limbic system in relation to fear behavior. *Neuroscience*, 141(2), 1047-1055.
- Gaylord, K. M., Cooper, D. B., Mercado, J. M., Kennedy, J. E., Yoder, L. H., & Holcomb, J. B. (2008). Incidence of posttraumatic stress disorder and mild traumatic brain injury in burned service members: preliminary report. *J Trauma*, 64(2 Suppl), S200-205.
- Herman, J. P., & Cullinan, W. E. (1997). Neurocircuitry of stress: central control of the hypothalamo-pituitary-adrenocortical axis. *Trends Neurosci*, 20(2), 78-84.
- Hoge, C. W., McGurk, D., Thomas, J. L., Cox, A. L., Engel, C. C., & Castro, C. A. (2008). Mild traumatic brain injury in U.S. Soldiers returning from Iraq. *N Engl J Med*, 358(5), 453-463.
- Judge S.J., Gartside S.E. (2006). Firing of 5-HT neurones in the dorsal and median raphe nucleus in vitro shows differential  $\alpha$ 1-adrenoceptor and 5-HT1A receptor modulation. *Neurochemistry International* 48:100-107.
- Kennedy, J. E., Jaffee, M. S., Leskin, G. A., Stokes, J. W., Leal, F. O., & Fitzpatrick, P. J. (2007). Posttraumatic stress disorder and posttraumatic stress disorder-like symptoms and mild traumatic brain injury. *J Rehabil Res Dev*, 44(7), 895-920.
- Liberzon, I., King, A. P., Britton, J. C., Phan, K. L., Abelson, J. L., & Taylor, S. F. (2007). Paralimbic and Medial Prefrontal Cortical Involvement in Neuroendocrine Responses to Traumatic Stimuli. *Am J Psychiatry*, 164(8), 1250-1258.
- Lowry, C. A., Hale, M. W., Evans, A. K., Heerkens, J., Staub, D. R., Gasser, P. J., & Shekhar, A. (2008). Serotonergic systems, anxiety, and affective disorder: focus on the dorsomedial part of the dorsal raphe nucleus. *Ann N Y Acad Sci*, 1148, 86-94.
- Lukkes, J., L., Watt, M., J, Lowry, C., A., & Forster, G., L. . (2009a). Consequences of post-weaning social isolation on anxiety behavior and related neural circuits in rodents. *Frontiers in Behavioral Neuroscience*, 3(1), 1-12.

- Lukkes, J. L., Mokin, M. V., Scholl, J. L., & Forster, G. L. (2009b). Adult rats exposed to early-life social isolation exhibit increased anxiety and conditioned fear behavior, and altered hormonal stress responses. *Horm Behav*, 55(1), 248-256.
- Milad, M. R., Orr, S. P., Lasko, N. B., Chang, Y., Rauch, S. L., & Pitman, R. K. (2008). Presence and acquired origin of reduced recall for fear extinction in PTSD: results of a twin study. *J Psychiatr Res*, 42(7), 515-520.
- Milad, M. R., Rauch, S. L., Pitman, R. K., & Quirk, G. J. (2006). Fear extinction in rats: implications for human brain imaging and anxiety disorders. *Biol Psychol*, 73(1), 61-71.
- Orr, S. P., Metzger, L. J., Lasko, N. B., Macklin, M. L., Peri, T., & Pitman, R. K. (2000). De novo conditioning in trauma-exposed individuals with and without posttraumatic stress disorder. *J Abnorm Psychol*, 109(2), 290-298.
- Quirk, G. J., Likhtik, E., Pelletier, J. G., & Pare, D. (2003). Stimulation of medial prefrontal cortex decreases the responsiveness of central amygdala output neurons. *J Neurosci*, 23(25), 8800-8807.
- Rauch, S. L., Shin, L. M., & Phelps, E. A. (2006). Neurocircuitry models of posttraumatic stress disorder and extinction: human neuroimaging research--past, present, and future. *Biol Psychiatry*, 60(4), 376-382.
- Stam, R. (2007). PTSD and stress sensitisation: A tale of brain and body: Part 1: Human studies. *Neuroscience & Biobehavioral Reviews*, 31(4), 530-557.
- Watt, M. J., Burke, A. R., Renner, K. J., & Forster, G. L. (2009). Adolescent male rats exposed to social defeat exhibit altered anxiety behavior and limbic monoamines as adults. *Behav Neurosci*, 123(3), 564-576.

#### **Appendix:**

A copy of the Meyer et al submitted manuscript follows.

Meyer, D.L., Davis, D.R., Barr, J.L., Manzerra, P., and Forster, G.L. Mild Traumatic Brain Injury in the Rat Alters Neuronal Number in the Limbic System and Increases Conditioned Fear and Anxiety-like Behaviors. *Experimental Neurology*, in review.

**Mild Traumatic Brain Injury in the Rat Alters Neuronal Number in the Limbic System and Increases Conditioned Fear and Anxiety-like Behaviors.**

Danielle L. Meyer<sup>1</sup>, Daniel R Davies<sup>1</sup>, Jeffrey L. Barr<sup>1,2</sup>, Pasquale Manzerra<sup>1</sup>  
and Gina L. Forster<sup>1\*</sup>

<sup>1</sup>*Neuroscience Group, Division of Basic Biomedical Sciences, Sanford School of Medicine, University of South Dakota, Vermillion, SD, 57069, USA.*

<sup>2</sup>*Department of Pharmacology, Temple University School of Medicine, Philadelphia, PA, 19140, USA*

Number of words in Abstract: 238

Number of Tables: 4

Number of Figures: 7

**\*Corresponding Author**

Gina L. Forster, Ph.D.

Division of Basic Biomedical Sciences

Sanford School of Medicine

University of South Dakota

414 E. Clark St.

Vermillion, SD, 57069

USA

Telephone: (605) 677 6883

Fax: (605) 677 6381

email: gforster@usd.edu

## Abbreviations

ACC	anterior cingulate cortex
BLA/LA	basolateral/lateral amygdala
CeA	central nucleus of the amygdala
Cg	cingulate cortex
Cx	cortex
DG	dentate gyrus
EPM	elevated plus maze
GAD	Generalized anxiety disorder
IL	infralimbic cortex
MeA	medial amygdala
mPFC	medial prefrontal cortex
mTBI	mild traumatic brain injury
PBS	phosphate-buffered saline
PrL	prelimbic cortex
PTSD	posttraumatic stress disorder
RT	room temperature
SNK	Student-Newman-Keuls

## **Abstract**

Recent reports suggest that experiencing a mild closed head trauma or mild traumatic brain injury (mTBI) is associated with a greater incidence of anxiety disorders. Dysfunction of limbic structures, such as the medial prefrontal cortex, amygdala and hippocampus, is associated with the symptoms of anxiety disorders. Therefore, the goal of the current studies was to characterize the consequences of closed mTBI on these limbic structures and associated fear and anxiety-related behaviors. A weight-drop procedure was employed to induce mTBI in male rats. Rats were transcardically perfused 4 or 9 days following exposure to mTBI or control procedures, and neuronal number, brain region area, and the number of apoptotic cells in each region were determined. In separate groups of rats, the effects of mTBI on anxiety-like behaviors, motor function, nociception, and acquisition, retention and extinction of contextual fear were also assessed. Findings suggest that mTBI was associated with significant neuronal cell loss in the CA1 region of the dorsal hippocampus and increased cell number in subregions of the amygdala, both of which appear to be related to alterations to apoptosis in these regions following mTBI. Furthermore, mTBI increased expression of anxiety-like behaviors and conditioned fear, with no effect on motor performance or nociception. Overall, a single impact to the skull to mimic mTBI in rats produces discrete alterations to neuronal numbers within the limbic system and specific emotional deficits, providing a potential neurobiological link between mTBI and anxiety disorders.

## **Key Words**

Mild traumatic brain injury; Concussive injury; Apoptosis; Hippocampus; Amygdala; Anxiety; Posttraumatic stress disorder.

## **Introduction**

Mild traumatic brain injury (mTBI) is characterized by a non-penetrating direct or indirect blow to the head, accompanied by loss of consciousness for less than 30 min and/or alterations to mental state (Bay and Liberzon, 2009; Bonne et al., 2003; Gaylord et al., 2008; Hoge et al., 2008; Moore et al., 2006). Up to 1.5 million

individuals in the US suffer from a mTBI annually, and these injuries most often occur in young males (Moore et al., 2006). While most individuals fully recover from mTBI within 12 weeks, estimates suggest that 7-30% (even up to 60% in some reports) of individuals suffer from a post-concussive syndrome that comprises physical, cognitive and emotional symptoms resulting in impairment for months to years (Bay and Liberzon, 2009; Belanger et al., 2007; Kennedy et al., 2007; Lewine et al., 2007; Ptito et al., 2007). Specifically, 23% of individuals that sustain mild brain injury suffer from an anxiety disorder as a result of the injury, most often generalized anxiety disorder (GAD) or posttraumatic stress disorder (PTSD) (as reviewed by Moore et al., 2006). Furthermore, a recent survey of US Army infantry soldiers revealed close to 15% suffered a mTBI, and of those, 44% also met the diagnosis criteria for PTSD (Hoge, et al., 2008). Distinguishing symptoms of post-concussive syndrome from those of anxiety disorders such as GAD or PTSD can be difficult, given many overlapping non-specific symptoms such as irritability, insomnia and amnesia (Gaylord et al., 2008; Moore et al., 2006). However, the potential for comorbidity of post-concussive syndrome with anxiety disorders has recently been discussed (e.g. Bryant, 2008; Gaylord et al., 2008; Hoge et al., 2008; Kennedy et al., 2007; Moore et al., 2006).

Brain regions susceptible to shearing and bruising during a mTBI incident involve the frontal pole and parts of the limbic system including the amygdala and hippocampus, which are also important regions for processing emotion and regulating behavioral and physiological responses to stressors (Bryant, 2008; Kennedy et al., 2007). The amygdala is a key structure involved in emotional processing and activating stress responses, and plays an important role in acquisition and expression of fear conditioning (Goosens and Maren, 2001; Herman et al., 2005). Functionally, a large number of imaging studies with various PTSD populations show hyperactivity of the amygdala in response to negatively-valenced emotive stimuli when compared to non-PTSD controls (e.g. Armony et al., 2005; Liberzon et al 1999; Milad et al., 2006; Rauch et al., 2000, 2006; Shin et al., 2004; 2005). In contrast to the amygdala, many functional imaging studies with PTSD subjects show hypoactivity within the anterior cingulate cortex (ACC; Brodman areas 24, 25, 32 and 33) during emotive imagery or when subjects are required to suppress trauma-related information in order to produce a correct response (e.g., Bremner et al., 2004; Hopper et al., 2007; Milad et al., 2006; Shin et al, 2001, 2005). Likewise, the hippocampal activation during the presentation of negatively-valenced words is attenuated in PTSD

populations (Bremner et al., 2003). Interestingly, the ACC (or the equivalent medial prefrontal cortex [mPFC] of rats; Milad et al., 2006) and hippocampus are thought to play a role in reducing stress responsiveness (Herman et al., 2005), and the mPFC in particular inhibits amygdala activity and output (Milad et al., 2006; Quirk et al., 2003). During heightened anxiety states, there appears to be inadequate top-down inhibition of the amygdala by the ACC or mPFC (Milad et al., 2006; Rauch et al., 2006). Therefore, it is conceivable that alterations to ACC (mPFC), hippocampus and amygdala function by mTBI could result in symptoms that resemble PTSD or other anxiety disorders.

To directly test the above hypothesis, a suitable animal model is required. While there are many experimental models of TBI such as fluid percussion or controlled cortical impact, most require section of the skull to be removed and direct trauma to the brain tissue, producing moderate to severe TBI (Morales et al., 2005). A modified weight drop method for adult rats and mice allows for a mild closed head injury that more closely resembles a human concussion injury. Specifically, this method does not lead to gross morphological damage to the rat brain (Henninger et al., 2005, 2007; Tang et al., 1997b), similar to what is often seen with human post-concussive syndrome (Anderson et al., 1996; Belanger et al., 2007; Wallesch et al., 2001). However, this injury results in discrete cell loss in the rat hippocampus as measured 9-14 days after the injury, accompanied by deficits in spatial learning and memory (Fujiki et al., 2008; Henninger et al., 2005; Tang et al., 1997a,b). These findings suggest that mTBI can result in discrete damage to the limbic system to have functional behavioral consequences. However, cell loss in other limbic regions that could mediate anxiety-like states have not been examined, nor have anxiety or fear behaviors been assessed following mTBI in an animal model. Using an equivalent model of mTBI in young adult male rats, we tested whether this injury resulted in alterations to neuronal number and cell death in other regions of the limbic system (mPFC and subregions of the amygdala) in addition to the hippocampus, and hypothesized that disruption in the limbic system would result in increased fear and anxiety following mTBI.

## **Materials and methods**

### *Animals*

The experiments conducted were approved by the Institutional Animal Care and Use Committee of South Dakota and the US Army Medical Research and Materiel Command Animal Care and Use Office, and were in accordance with the National Institutes of Health Guide for the Care and Use of Laboratory Animals. All efforts were made to minimize animal suffering, and to reduce the number of animals used.

Sixty-eight young adult male Sprague-Dawley rats (8-12 weeks old, Animal Resource Center, The University of South Dakota, Vermillion, South Dakota) were housed in pairs at a constant room temperature (22°C, 60% relative humidity) and with a reverse 12 h light: 12 h dark cycle (lights off at 10:00 am). Food and water were available *ad libitum*. Rats within each pair were randomly assigned to a weight-drop (mTBI) or sham surgery (control) group. All behavioral testing was conducted at least 1 hour after the onset of the dark phase (active phase) of the light cycle in dark rooms illuminated by red lighting.

#### *Surgery to Induce mTBI*

The laboratory-made weight drop apparatus used in these experiments was based on that used by Henninger et al. (2005, 2007) and Fujiki et al. (2008) to induce mTBI in adult rats. The following parameters were calibrated to induce a mild head injury in the absence of skull fractures, subdural, subarachnoid, intraventricular or brain hemorrhages, lesions or contusions (Henninger et al., 2005; Tang et al., 1997b) as determined by pilot studies examining the brain and skull at 1 hr, 24 hrs, 4 days and 9 days following injury. The apparatus had a Plexiglas® tube (inner diameter = 11 mm, length = 100 cm) and holes were drilled at 2 cm intervals to minimize friction. A 175 g cylindrical brass weight (10 mm diameter) was allowed to freely drop through the tube onto a cylindrical polyacetal transducer rod (diameter = 10 mm, weight = 32.6 g, length = 15.75 cm). The weight was dropped from a distance of 42 cm by pressing the release on the solenoid, ensuring consistency between drops.

Rats were induced with 4% isoflurane in 3.0 L/min O<sub>2</sub>, and the isoflurane was reduced to 3% throughout the rest of the surgical process. After induction, rectal temperature was monitored and maintained at 37°±0.5°C by a feedback system heating pad (Harvard Apparatus, Holliston, MA). Pulse, breath rate, and oxygen saturation were monitored using a foot-clip oximeter device (Stoelting, Wood Dale, IL). The skull was exposed using a midline incision and the rat was moved under the weight drop apparatus in the prone position. The



transducer rod was positioned on midline posterior to bregma with the head secured between two Plexiglas® blocks and held manually in the back to prevent any movement. Adjustments were then made to ensure the head was positioned level was at a 90 degree angle to the transducer. Once correctly positioned, the weight was released, and the transducer rod held immediately following contact to avoid rebound injuries. The wound was then closed using wound clips and the animal was removed from isoflurane. Rats were given an intramuscular injection of the analgesic ketoprofen (5 mg/kg) and monitored for a righting reflex. Control rats underwent the same surgical procedures for the same length of time under isoflurane, in the absence of the weight drop.

### *Histology*

All animals used for histological analysis were transcardially perfused either four or nine days (n = 7 per group at each time point) following mTBI or control surgery. The nine day time point was chosen to be consistent with the other previous reports of mTBI in adult rats that assessed cell number in the dorsal hippocampus (Henninger et al., 2005; Fujiki et al., 2008), whereas the four day time point was chosen to represent an intermediate time point to assess the progression of changes in cell number.

Rats were anesthetized using sodium pentobarbital (100 mg/kg, ip.) then perfused with phosphate-buffered saline (PBS, pH 7.4; room temperature [RT]), followed by 4% paraformaldehyde (pH 7.4, 4°C). Following perfusion, brains were post-fixed for 1 h in 4% paraformaldehyde (4°C) and then store in 25% sucrose for 2 days at 4°C. Brains were then embedded in a gelatin embedding solution (10% gelatin, 8% sucrose) and were stored in 25% sucrose for at least 2 days at 4°C. Brains were sectioned using a sliding microtome in the coronal plane, anterior to posterior at 60 µm with every third section saved. Sections were stored in cryoprotectant at -20° C until processing.

Sections were processed for either cell counting or immunohistochemistry to detect apoptotic cells. Sections used for cell counting were mounted on gelatin-coated slides, dehydrated, stained with 0.5% cresyl violet (Henninger et al., 2005) and coverslipped with cyto seal (Richard-Allan Scientific, Kalamazoo, MI). Immunohistochemistry sections were processed by co-labeling for NeuN (a neuron specific nuclear protein as a marker of mature neurons; Mullen et al., 1992) and TUNEL for apoptotic cells (Tashlkov et al., 2007). Sections were rinsed in 0.1 M PBS, incubated in mouse anti-NeuN (1:750, Chemicon International Inc, Temecula, CA)

at 4 °C for 20 h, rinsed 3X for 5 min in 0.1 M PBS and incubated in Cy2-conjugated goat anti-mouse secondary antibody (1:200, Jackson ImmunoResearch, West Grove, PA) for 2 h at RT. Sections were mounted on gelatin-coated slides, air-dried, and then TUNEL staining was performed using an Apoptag red detection kit (Millipore, Temecula, CA; Barr et al., 2010). Slides were then dehydrated, and coverslipped with cyto seal (Richard-Allan Scientific).

Sections were examined using a Zeiss Axioskop 2 mot-plus microscope and all measures and counts were obtained blind to treatment. Limbic areas of interest included the sub-regions of the dorsal and ventral hippocampus, mPFC, amygdala, and the cortex below the site of injury (comprising the retrosplenial, M1, M2 and S1 trunk region cortices) as defined by Paxinos and Watson (1998). The volume of each brain region of interest was measured from cresyl violet stained sections at 2.5x magnification by the Cavalieri method (Slomianka and West, 2005), using points spaced at 10 mm, 12.5 mm, or 20 mm intervals along the x and y axis. The area associated with each point was 100 mm<sup>2</sup>, 156.25 mm<sup>2</sup>, or 400 mm<sup>2</sup> respectively. The optical dissector method (Slomianka and West, 2005; West, 1993) was used to estimate how many neurons were present per region in cresyl violet stained sections at 20x magnification, using a 3 mm x 3 mm counting frame applied 5 or 10 times per region depending on the region size. Since the level TUNEL-labeled cells are low in number (Barr et al., 2010), the total number of positive cells were counted from NeuN-TUNEL stained sections within a counting frame that outline the region of interest on each section (defined by NeuN staining) as according to the method of Barr et al. (2010). Zeiss AxioVision software v4.5 was used to draw the counting frame and provided the area (mm) sampled. The number of TUNEL-positive cells per area sampled was calculated for each region of interest.

### *Contextual Fear Conditioning*

Rats (n = 10 per group) were tested for contextual fear conditioning beginning 8 days after the mTBI or sham surgery procedure. The procedures follow those of Hunsaker and Kesner (2008) who demonstrated that the dorsal CA1 was important for the retrieval of contextual fear conditioning, given that mTBI resulted in loss of dorsal CA1 neurons (see Figure 2B). On the first day of testing (encoding), rats were placed in the foot shock chamber with an overhead camera (30cm x 30cm; Noldus Information Technology, Wageningen, The

Netherlands) within a sound-attenuating chamber (Med-Associates, St. Albans, VT) for 2 min prior to delivery of 10 electric foot shocks (2 s duration, 0.75mA) separated by 74 s. Shocks were delivered through the grid floor and were controlled by Ethovision 3.1. (Noldus Technologies). Video footage was recorded by Mediacruise (Canopus Co., Ltd., Nevada City, CA). Following the 10 foot shocks, animals remained in the chamber for an additional 2 min. Twenty-four hours later, rats were tested for contextual conditioning by being placed in the same chamber without shocks administered for a total of 8 min. Extinction of the conditioned fear response was examined on the third and fourth days, where the rat was again placed in the context for 8 min. Freezing behavior from video footage during the foot shock on encoding day, conditioning test and extinction days was hand-scored by a well-trained observer blind to treatment using Ethovision 3.1. Freezing was defined as total immobility of the animal with the exception of the very limited movement necessary for respiration (Forster et al., 2006).

#### *Elevated Plus Maze Testing*

A separate group of rats (n = 10 per group) were tested for unconditioned anxiety-like behaviors 6 days following mTBI or sham surgery using the elevated plus maze (EPM; Vuong et al., 2010). The maze consisted of two intersecting runways (12 cm wide x 100 cm long) which were perpendicular from each other. Two of the runways had no walls while the others had high walls (40 cm high), with the maze elevated 1 m from the floor (Noldus Information Technology, Wageningen, The Netherlands). The test started with a rat being placed in the center of the maze facing a closed arm, and the rat was allowed to freely explore for 5 min. Latency to enter an open arm, cumulative time spent in each arm, and total distance moved within the maze were automatically scored by Ethovision XT v5.1 (Noldus Technologies).

#### *Locomotion*

Rats that had been used for EPM testing (n = 10 per group) were tested for locomotor behavior in the foot shock chambers 7 days following mTBI or sham surgeries. This was conducted to ensure that any differences observed in the conditioned foot shock experiment were not due to differences in activity within the chambers between mTBI and control groups. Animals were placed in the same chambers used for the foot shock

experiment as described above and allowed to freely move around the chamber for 30 min. Total distance moved was scored automatically (Ethovision 3.1, Noldus Technologies).

### *Rotarod Testing*

Rats that had been used for EPM and locomotion testing (n = 10 per group) were trained and tested on the rotarod for motor strength and coordination starting day 8 post-surgery. This test was used to ensure that the weight drop procedure did not produce gross motor deficits that would suggest an injury greater than mTBI (Henninger et al., 2005). The rotarod consisted of a 9.5 cm diameter barrel positioned 23 cm above a transducer platform (Stoelting, Wood Dale, IL). Animals were given five training trials of 3 min for each of two training days, allowing for at least 5 min of rest between each trial. Each training trial was started with a barrel speed of 5 rpm which accelerated to the final speed of 15 rpm over the first 90 sec. On the test day, rats were placed on the rotarod with the same rpm and acceleration rate as for the training days (modified from Malherbe et al., 2009), with the test length remaining congruent at 2 min. Rats were allowed three tests, and latency to fall onto the transducer platform was automatically recorded by software (IITC INC./Life Science, Woodland Hills, CA). The average latency over the three trials was calculated for analysis.

### *Tail-withdrawal Test*

Finally at 12 days post-surgery, rats that had been exposed to EPM, locomotion and rotarod testing (n = 10 per group) went through the tail-withdrawal test as according to Lukkes et al. (2009). This was conducted to ensure that any differences in foot shock reactivity or conditioning could not be attributed to differences in nociception between mTBI and control groups (Lukkes et al., 2009). Rats were acclimated to the restraining tube (20.3 x 8.9 x 5.7cm; Braintree Scientific, Inc, Braintree, MA) for 5 min per day on two consecutive days previous to testing. On the test day, the distal 10 cm of the tail was immersed in 50±0.5 °C water. The temperature of the water was maintained using a thermostat controlled water bath. The latency to withdrawal the tail from the water was recorded by a second experimenter blind to treatment using a stopwatch (0.01 s time resolution). Three trials were performed with 30 s between each trial, with the average latency over the three trials calculated.

## Data Analysis

Initially, all data was subjected to the Grubbs outlier test (Feng et al., 2009), which resulted in the removal of 22 statistical outlier data points from the 1092 total data points from the histology experiments, and 2 statistical outlier data points from the 200 total data points from the behavioral experiments ( $P < 0.05$ ). Following this, one-way ANOVA were used to analyze all cell counts and behavioral data. The exceptions to this were the physiological parameters recorded during surgery and the fear conditioning data, which were analyzed using separate two-way ANOVA with time as a repeated measure, followed by Student-Newman-Keuls (SNK) *post-hoc* test for between-subject pairwise comparisons or Holm-Sidak *post-hoc* test for multiple pairwise comparisons over time. The significance level for all analyses was set at  $P < 0.05$ , and all analyses were performed using Sigma Stat v3.5.

## Results

### *Effects of mTBI on Physiological Parameters*

Control (21.67  $\pm$  0.73 min) and mTBI (21.61  $\pm$  0.94 min) rats spent similar amount of time under isoflurane during the surgical period ( $F_{(1,60)} = 0.003$ ,  $P = 0.957$ ). Physiological parameters were recorded following the mTBI or sham procedures during the surgery and over the subsequent recovery period between removal of isoflurane and return of righting reflex, with few differences between control and mTBI rats observed (Table 1). For oxygen saturation, there was a significant effect of time ( $F_{(5,237)} = 12.380$ ,  $P < 0.001$ ) but no significant effect of mTBI treatment ( $F_{(1,50)} = 0.0484$ ,  $P = 0.490$ ) nor a significant interaction between treatment and time ( $F_{(5,237)} = 1.751$ ,  $P = 0.124$ ). Oxygen saturation significantly decreased over time for both control rats (4-8 min post-sham procedures; Holm-Sidak  $P < 0.05$ ) and mTBI rats (6-8 min post-mTBI; Holm-Sidak  $P < 0.05$ ) (Table 1). Heart rate remained unaffected, with no significant effect of treatment ( $F_{(1,50)} = 0.001$ ,  $P = 0.988$ ), time ( $F_{(5,237)} = 1.825$ ,  $P = 0.109$ ) nor an interaction between treatment and time ( $F_{(5,237)} = 1.374$ ,  $P = 0.255$ ). However, there was a significant effect of time ( $F_{(5,237)} = 8.423$ ,  $P < 0.001$ ) and a significant interaction between time and mTBI treatment ( $F_{(5,237)} = 2.582$ ,  $P = 0.027$ ) on breath rate. Breath rate was significantly

higher at 6 and 8 min post-mTBI, and 8 min post-sham procedures (Holm-Sidak  $P < 0.05$ ) as compared to pre-procedure rates (Table 1). There was also a significant difference between control and mTBI in breath rate at 6 min post- procedure (SNK  $P < 0.05$ ; Table 1). Finally, mTBI rats ( $5.27 \pm 0.30$  min) took significantly longer to exhibit a righting reflex following the removal of isoflurane as compared to control rats ( $4.31 \pm 0.24$  min) ( $F_{(1,60)} = 6.195$ ,  $P = 0.016$ ).

### *Effects of mTBI on the Area of Specific Limbic Regions*

The area ( $\text{mm}^2$ ) of most limbic brain regions studied was not affected by mTBI, with the exception of the basolateral/lateral amygdala (BLA/LA) and the medial amygdala (MeA) (Table 2). The area of the BLA/LA was not affected by mTBI at 4 days post-injury ( $F_{(1,9)} = 0.177$ ,  $P = 0.689$ ), but mTBI did result in a significant increase in the area of the BLA/LA 9 days following injury ( $F_{(1,9)} = 7.382$ ,  $P = 0.026$ ; Table 2). Likewise, the area of the MeA was not affected by mTBI 4 days post injury ( $F_{(1,9)} = 1.267$ ,  $P = 0.293$ ), but there was a significant increase in the area of this region at 9 days post injury ( $F_{(1,9)} = 7.812$ ,  $P = 0.023$ ; Table 2).

### *Effect of mTBI on the Total Number of Neurons in Specific Limbic Regions*

Overall, mTBI had little effect on the total number of neurons in the limbic brain regions measured (Table 3), with the exception of the dorsal hippocampus and the amygdala (Figures 1-2). Specifically, the BLA/LA of mTBI rats exhibited increased neuronal number 9 days following injury ( $F_{(1,9)} = 6.201$ ,  $P = 0.038$ ; Figure 1B) that was not seen at 4 days post-injury ( $F_{(1,8)} = 0.008$ ,  $P = 0.931$ ; Figure 1A). Likewise, there was no significant effect of mTBI at 4 days post-injury in the MeA ( $F_{(1,9)} = 2.012$ ,  $P = 0.194$ ; Figure 1C), with a significant increase in neuronal number within this same region at 9 days after mTBI ( $F_{(1,9)} = 9.348$ ,  $P = 0.016$ ; Figure 1D). In contrast, mTBI had no effect on the total number of neurons in the CeA at 4 ( $F_{(1,9)} = 0.001$ ,  $P = 0.970$ ; Figure 1E) or at 9 days after injury ( $F_{(1,10)} = 0.173$ ,  $P = 0.686$ ; Figure 1F).

Opposite to the amygdala, mTBI led to a decrease in the total number of neurons in the CA1 region of the dorsal hippocampus 9 days after injury ( $F_{(1,11)} = 5.242$ ,  $P = 0.043$ ; Figure 2B), but not at 4 days ( $F_{(1,11)} = 0.104$ ,  $P = 0.753$ ; Figure 2A). In contrast, mTBI had no effect on total neuronal number in the dorsal CA3 region at 4 days ( $F_{(1,11)} = 0.062$ ,  $P = 0.807$ ; Figure 2C) or at 9 days post-injury ( $F_{(1,12)} = 0.002$ ,  $P = 0.964$ ; Figure 2D),

nor on the total number of neurons in the dorsal DG at 4 ( $F_{(1,10)} = 4.329$ ,  $P = 0.064$ ; Figure 2E) or 9 days post-injury ( $F_{(1,12)} = 0.307$ ,  $P = 0.590$ ; Figure 2F).

### *Effect of mTBI on Apoptosis in Specific Limbic Regions*

The level of apoptosis did not differ between control and mTBI groups in a number of the limbic brain regions measured (Table 4), with the exception of the amygdala and the dorsal hippocampus (Figures 3-4).

Specifically, the density of apoptotic cells in two subregions of the amygdala (Figure 3) was significantly decreased following mTBI. The BLA/LA had decreased density of apoptotic cells following mTBI at both 4 days ( $F_{(1,10)} = 5.712$ ,  $P = 0.041$ ; Figure 3A) and 9 days ( $F_{(1,11)} = 7.193$ ,  $P = 0.021$ ; Figure 3B). Similarly, there was a decreased density of apoptotic cells in the MeA at both 4 days ( $F_{(1,10)} = 41.409$ ,  $P < 0.001$ ; Figure 3C) and 9 days ( $F_{(1,11)} = 5.227$ ,  $P = 0.043$ ; Figure 3D) post-mTBI. There was no significant effect of mTBI on apoptosis in the CeA at 4 days ( $F_{(1,10)} = 0.0452$ ,  $P = 0.836$ ; Figure 3E) or at 9 days ( $F_{(1,11)} = 0.104$ ,  $P = 0.754$ ; Figure 3F).

Apoptosis was increased in two subregions of the dorsal hippocampus following mTBI (Figure 4). There was a significant increase in density of apoptotic cells in the dorsal CA1 at 4 days ( $F_{(1,11)} = 5.305$ ,  $P = 0.042$ ; Figure 4A) post-mTBI, but not at 9 days ( $F_{(1,11)} = 2.903$ ,  $P = 0.116$ ; Figure 4B). However, there was no effect of mTBI on apoptosis in the dorsal CA3 as measured at 4 days ( $F_{(1,11)} = 1.135$ ,  $P = 0.310$ ; Figure 4C), or at 9 days ( $F_{(1,11)} = 0.341$ ,  $P = 0.571$ ; Figure 4D). Similar to the dorsal CA1, mTBI increased the density of apoptotic cells in the dorsal DG at 4 days ( $F_{(1,11)} = 6.165$ ,  $P = 0.030$ ; Figure 4E), but not 9 days ( $F_{(1,11)} = 0.193$ ,  $P = 0.669$ ; Figure 4F).

### *Effects of mTBI on Contextual Fear Conditioning and Nociception*

Overall, mTBI increased the acquisition of contextual fear conditioning without affecting extinction of this response, or altering nociception (Figure 5). During conditioning, there was no significant effect of mTBI on the percent of time spent freezing ( $F_{(1,17)} = 1.195$ ,  $P = 0.290$ ; Figure 5A). However, for the conditioning test and extinction days (Figure 5B), there was a significant effect of mTBI ( $F_{(1,18)} = 5.597$ ,  $P = 0.029$ ), and a significant effect of test day ( $F_{(2,31)} = 47.495$ ,  $P < 0.001$ ). *Post hoc* analysis revealed mTBI rats exhibited

significantly increased time spent freezing on the conditioning test day as compared to control rats (SNK  $P = 0.029$ ; Figure 5B). Furthermore, both mTBI and control rats spent significantly less time freezing on extinction day 1 (Holm-Sidak  $P < 0.001$ ) and extinction day 2 (Holm-Sidak  $P < 0.001$ ) when compared to the conditioning test day, but there was no significant difference in the degree of freezing behavior between mTBI and control groups on extinction days (SNK  $P > 0.05$ ; Figure 5B). When nociception was testing using the tail withdrawal test, there was no significant difference between control and mTBI groups ( $F_{(1,18)} = 1.292$ ,  $P = 0.271$ ; Figure 5C).

#### *Effects of mTBI on Anxiety-like Behavior*

Testing on the EPM revealed that mTBI also resulted in increased unconditioned anxiety-like behaviors (Figure 6). Specifically, mTBI resulted in significantly higher latency to enter an open arm ( $F_{(1,11)} = 10.55$ ,  $P = 0.009$ ; Figure 6A), and reduced time spent in the open arms of the maze ( $F_{(1,18)} = 9.431$ ,  $P = 0.007$ ; Figure 6B). These differences were not a result of decreased mobility following mTBI, since the distance moved in the entire maze was not significantly different between the two groups ( $F_{(1,18)} = 2.509$ ,  $P = 0.130$ ; Figure 6C).

#### *Effects of mTBI on Locomotion, Strength and Coordination*

The mTBI injury used in the current study did not lead to motoric deficits (Figure 7). There was no significant effect of mTBI on locomotor behavior ( $F_{(1,18)} = 3.413$ ,  $P = 0.082$ ; Figure 7A). Furthermore, strength and coordination as tested by time spent on the rotarod, was not affected by mTBI ( $F_{(1,18)} = 1.341$ ,  $P = 0.264$ ; Figure 7B).

### **Discussion**

Similar to the findings of Henninger et al. (2005), mTBI in an adult rat model resulted in a significantly longer return of the righting reflex following the weight drop procedure, which was not a function of increased time under anesthesia as compared to control rats. However, the mTBI procedure did not result in gross motoric deficits when tested days after the injury. The injury did result in discrete changes in neuronal numbers in the



dorsal CA1, BLA/LA, and MeA, which was accompanied by alterations to apoptosis in these same regions. Furthermore, this mTBI procedure was associated with greater unconditioned anxiety and contextual fear conditioning. The changes in neuronal numbers, apoptosis and related behaviors did not appear to be due to observable hypoxia or ischemia during the mTBI event, particularly since the injury did not cause any bleeding within or around the brain, and saturated O<sub>2</sub> levels did not differ between sham and mTBI groups. Therefore, the mild impact to the skull appears to result in discrete changes to the limbic system and emotive behaviors that are apparent days following injury without obvious gross morphological damage to the brain or motoric deficits.

Previous (e.g.: Fujiki et al., 2008; Henninger et al., 2005; Tang et al., 1997b) and current findings suggest that the dorsal hippocampus is susceptible to neuronal loss following mild head injury. Specifically, mTBI injury of adult rats or mice often results in neuronal loss in the CA1 and CA3 regions of the dorsal hippocampus, as measured 9-14 days post-injury (Fujiki et al., 2008; Henninger et al., 2005; Tang et al., 1997b). The current study differs from some previous reports (e.g. Henninger et al., 2005; Tang et al., 1997b) but is similar to others (e.g., Fujiki et al., 2008) by observing significant cell loss in the dorsal CA1 region only, suggestive of a milder injury. However, the current study adds to previous findings by showing that up to 9 days is required to observe neuronal loss in the dorsal CA1 after mTBI, since this cell loss is not observable 4 days post-injury. Delayed neuronal loss in the dorsal CA1 may be a result of injury-induced onset of apoptotic mechanisms, since increased density of apoptotic cells in the CA1 region was observed 4 days post-injury. In support of this, mTBI in a mouse model leads to increased expression of proapoptotic proteins such p53 in whole brain homogenates and caspase 3, Bax and apoptosis-inducing factor in the hippocampus, 72 hours following injury (Tweedie et al., 2007; Tashlykov et al., 2009). Overall, the current findings complement others that suggest that the CA1 region of the dorsal hippocampus is often more susceptible to neuronal cell loss following perturbation (Schmidt-Kastner and Freund, 1991; Kreisman et al, 2000; Fujiki et al., 2008). Kreisman et al. (2000) suggest that increased susceptibility of CA1 neurons is a result of increased excitotoxic events in this region immediately after an ischemic or hypoxic event. While enhancement of excitatory synaptic activity and hyperactivity of CA1 neurons and regional CA1 increases in glucose metabolism have been observed immediately following moderate fluid percussive brain injury (Yoshino et al., 1992; Akasu et al.,

2002; Ooba et al., 2009), the mechanisms by which neurons in this region are susceptible to mTBI in the absence of ischemia or hypoxia require further examination.

The dorsal DG showed also increased apoptosis 4 days post-injury in the current study, but this did not manifest as decreased neuronal number at 4 or 9 days following mTBI. Other reports also suggest increased apoptosis in this region 72 hours following mTBI (Tashlykov et al., 2007, 2009). However, the lack of concordance between heightened apoptosis and ultimate neuronal number may be a result of the DG being a locus of adult neurogenesis (Ehninger and Kempermann, 2008), so that increased injury-induced apoptosis may be compensated for by increased neurogenesis in this region. Cell proliferation in the DG is rapidly induced following TBI induced via fluid percussion or cortical impact, and peaks between 3 and 7 days post injury (Dash et al., 2001; Emery et al., 2005; Sun et al., 2007). This increased production of cells leads to greater numbers of newly integrated dentate granule neurons (Emery et al., 2005; Sun et al., 2007) despite reduced survival rates (Sun et al., 2007). Therefore, increased injury-induced apoptosis may be compensated for by increased neurogenesis in this region.

The current findings also demonstrate for the first time that the amygdala is also susceptible to mTBI. In particular, mTBI resulted in increased neuronal numbers in the BLA/LA and the MeA 9 days post-injury, which is likely a result of decreased apoptosis in these regions as observed 4 days post-injury. Interestingly, decreased apoptosis was also observed in the BLA/LA and MeA at 9 days post-injury, suggesting that cell numbers in this region may continue to increase beyond the 9 day observation point. The area of each region was also significantly increased by 9 days post-injury, probably a function of increased neuronal number and decreased cell death. While not an area of focus in adult mTBI imaging studies, increased amygdala volume has also been observed in a 10 year follow up of childhood TBI (Beauchamp et al., 2011). An increase in neuronal number and decreased levels of apoptosis suggest that mTBI activates cell survival molecules such as bcl-2 (Clark et al., 1997), PKB/Akt (Noshita et al., 2002, Shapira et al., 2007, Zhang et al., 2006), and IGF-1/IGF-1R (Madathil et al., 2010, Rubovitch et al., 2010) to decrease programmed cell death in these sub regions of the amygdala. Interestingly, suppression of cell death in the amygdala has been reported in mice exposed to environmental enrichment (Okuda et al., 2009), suggesting that such a phenomenon might occur in response to both positive and negative perturbations.

Human studies suggest that mTBI increases the incidence of anxiety disorders, particularly PTSD and GAD (e.g. Moore et al., 2006). Using the EPM, the current study showed that rats exposed to mTBI exhibit increased latency to enter open arms and reduced time in open arms, independent of overall locomotion. This is indicative of increased unconditioned anxiety-like behaviors, suggesting that this may be a good animal model to investigate the neurobiological mechanisms by which mTBI results in GAD in some individuals. The amygdala and the hippocampus (via the septo-hippocampal system) have both distinct and overlapping roles in the expression of anxiety states, with the hippocampus playing a greater role in negative cognitive bias characterizing GAD while the amygdala appears responsible for heightened arousal associated with GAD (McNaughton and Corr, 2004). While changes to neuronal numbers cannot be directly related to function within the same regions without further experimentation, it is feasible that the altered neuronal numbers in the sub regions of the amygdala and dorsal hippocampus observed following mTBI result in an imbalance in activity that ultimately increases unconditioned anxiety behavior. This is supported for the amygdala in particular by human imaging studies that show larger amygdala volumes in patients that suffer from GAD (Etkin et al., 2009; Schienle et al., 2011), concordant with the larger area of amygdala sub regions following mTBI in the current study.

Contextual fear conditioning was also heightened by mTBI in the current study, independent of any effect of mTBI on nociception. Sufferers of PTSD also show heightened contextual fear conditioning in both experimental and natural settings (e.g. Grillon, 2002; Grillon and Morgan, 1999), suggesting that this rat model approximates some of the symptoms of PTSD. Alterations to the hippocampus and amygdala induced by mTBI may underlie the observed enhancement in contextual fear conditioning. For example, the dorsal CA1 is implicated in the expression of contextual fear conditioning, although lesions of this region cause impairment in the acquisition of contextual fear (Hunsaker and Kesner, 2008). One possible explanation is that disruption to normal circuitry via discrete cell loss in the CA1 results in enhanced contextual fear conditioning, as seen in the current study, while full abolition of the region (Hunsaker and Kesner, 2008) decreases this behavior. Alternatively, the BLA/LA and MeA sub regions of the amygdala play an important role in the acquisition and expression of contextual fear conditioning (Fanselow and Le Doux, 1999; Goosens and Maren, 2001; Helmstetter et al., 2008), and hyperactivity of the amygdala is associated with PTSD (Armony et al., 2005;

Liberzon et al 1999b; Milad et al., 2006; Rauch et al., 2000, 2006; Shin et al., 2004, 2005). Therefore, increased cell number in the amygdala induced by mTBI may result in greater activity in this region and heightened expression of contextual fear conditioning.

Human studies suggest that PTSD subjects also exhibit poorer extinction of conditioned fear responses, which is thought to be a function of frontal cortex hypofunction (Milad et al., 2006, 2008; Quirk et al., 2006). However, in the current study there was no effect of mTBI on extinction of contextual fear conditioning, matching a lack of effect of mTBI on the subregions of the mPFC. Therefore, the current rat model does not approximate this aspect of PTSD. The majority of incidents that would result in a mTBI have a stressful component to them (Moore et al., 2006), and recent evidence suggests that brain injury and chronic stress combined have greater effects on the brain and behavior (Kwon et al., 2011). Therefore, the ability of mTBI in the rat to more closely produce PTSD-like symptoms might be enhanced by concurrent exposure to psychological stress, and this possibility requires further testing.

### *Conclusions*

The present rat model established a direct link between mTBI and the development of increased fear conditioning and anxiety states that are similar to symptoms of GAD and PTSD. While the underlying neurobiology needs to be tested directly, the current findings suggest that mTBI-induced alterations to apoptosis and neuronal cell numbers in the dorsal hippocampus and the amygdala are associated with post-injury fear and anxiety states. Future work to establish the mechanisms by which mTBI induces discrete changes in neuronal populations, and how these manifest into emotive behavioral deficits, will significantly enhance the current understanding of the neurobiology underlying anxiety disorders following head injury.

### **Acknowledgements**

This work was supported by a South Dakota Board of Regents Competitive Research Grant, Department of Defense Grant # PT090761, and NIH P20 RR015567 which is a designated Center of Biomedical Research

Excellence (COBRE). We thank Jamie Scholl, Emily Reinbold, Dr. Michael Watt, Michael Olson and Dr.

Frances Day for their assistance with these experiments.

## References

- Akasu, T., Muraoka, N., Hasuo, H., 2002. Hyperexcitability of hippocampal CA1 neurons after fluid percussion injury of the rat cerebral cortex. *Neuroscience Letters*. 329, 305-308.
- Anderson, C.V., Wood, D.M.G., Bigler, E.D., Blatter, D. D., 1996. Lesion volume, injury severity, and thalamic integrity following head injury. *Journal of Neurotrauma*. 13, 59-65.
- Armony, J.L., Corbo, V., Clément, M.H., Brunet, A., 2005. Amygdala response in patients with acute PTSD to masked and unmasked emotional facial expression. *Am J Psychiatry*. 162, 1961-1963.
- Barr, J.L., Renner, K.J., Forster, G.L., 2010. Withdrawal from chronic amphetamine produces persistent anxiety-like behavior but temporally-limited reductions in monoamines and neurogenesis in the adult rat dentate gyrus. *Neuropharmacology*. 59, 395-405.
- Bay, E.H., Liberzon, I., 2009. Early stress response: a vulnerability framework for functional impairment following mild traumatic brain injury. *Res Theory Nurs Pract*. 23, 42-61.
- Belanger, H.G., Vanderploeg, R.D., Curtiss, G., Warden, D.L., 2007. Recent neuroimaging techniques in mild traumatic brain injury. *J Neuropsychiatry Clin Neurosci*. 19, 5-20.
- Bonne, O., Gilboa, A., Louzoun, Y., Kempf-Sherf, O., Katz, M., Fishman, Y., Ben-Nahum, Z., Krausz, Y., Bocher, M., Lester, H., Chisin, R., Lerer, B., 2003. Cerebral blood flow in chronic symptomatic mild traumatic brain injury. *Psychiatry Research Neuroimaging*. 124, 141-152.
- Bremner, J.D., Vermetter, E., Vythilingam, M., Afzal, N., Schmahl, C., Elzinga, B., Charney, D.S., 2004. Neural correlates of the classic color and emotional stroop in women with abuse-related posttraumatic stress disorder. *Biol Psychiatry*. 55, 612-620.
- Bremner, J.D., Vythilingam, M., Vermetter, E., Southwick, S.M., McGlashan, T., Staib, L.H., Soufer, R., Charney, D.S., 2003. Neural correlates of declarative memory for emotionally valenced words in women with posttraumatic stress disorder related to early childhood sexual abuse. *Biol Psychiatry*. 53, 879-889.
- Bryant, R.A., 2008. Disentangling mild traumatic brain injury and stress reaction. *N Engl J Med*. 358, 525-527.
- Bryant, R.A., Felmingham, K., Kemp, A., Das, P., Hughes, G., Peduto, A., Williams, L., 2008. Amygdala and ventral anterior cingulate activation predicts treatment response to cognitive behavior therapy for post-traumatic stress disorder. *Psychological Medicine*. 38, 555-561.
- Clark, R.S., Chen, J., Watkins, S.C., Kochanek, P.M., Chen, M., Stetler, R.A., Loeffert, J.E., Graham, S.H., 1997. Apoptosis-suppressor gene bcl-2 expression after traumatic brain injury in rats. *J. Neurosci*. 17, 9172-9182.
- Dash, P.K., Mach, S.A., Moore, A.N., 2001. Enhanced neurogenesis in the rodent hippocampus following traumatic brain injury. *J Neuroscience Research* 63, 313-319.
- Ehninger, D., Kempermann, G., 2008. Neurogenesis in the adult hippocampus. *Cell and Tissue Research*. 331, 243-250.
- Emery, D.L., Fulp, C.T., Saatman, K.E., Schutz, C., Neugebauer, E., McIntosh, T.K., 2005. Newly born granule cells in the dentate gyrus rapidly extend axons into the hippocampal CA3 region following experimental brain injury. *J Neurotrauma* 22:978-988.

- Etkin, A., Prater, K.E., Schatzberg, A.F., Menon, V., Greicius, M.D., 2009. Disrupted amygdalar subregion functional connectivity and evidence of a compensatory network in generalized anxiety disorder. *Archives of General Psychiatry*. 66, 1361-1372.
- Fanselow, M.S., LeDoux, J.E, 1999. Why we think plasticity underlying Pavlovian fear conditioning occurs in the basolateral amygdala. *Neurons*. 23, 229-232.
- Feng, N., Telefont, M., Kelly, K.J., Orchinik, M., Forster, G.L., Renner, K.J., Lowry, C.A., 2009. Local perfusion of corticosterone in the rat medial hypothalamus potentiates D-fenfluramine-induced elevations of extracellular 5-HT concentrations. *Hormones and Behavior*. 56, 149-157.
- Forster, G.L., Feng, N., Watt, M.J., Korzan, W.J., Mouw, N.J., Summers, C.H., Renner, K.J., 2006. Corticotropin-releasing factor in the dorsal raphe elicits temporally distinct serotonergic responses in the limbic system in relation to fear behavior. *Neuroscience*. 141, 1047-1055.
- Fujiki, M., Kubo, T., Kamida, T., Sugita, K., Hikawa, T., Abe, T., Ishii, K., Kobayashi, H., 2008. Neuroprotective and anti-amnesic effect of donepezil, nicotinic acetylcholine-receptor activator, on rats with concussive mild traumatic brain injury. *J. Clin. Neurosci*. 15, 791-796.
- Gaylord, K.M., Cooper, D.B., Mercado, J.M., Kennedy, J.E., Yoder, L.H., Holcomb, J.B., 2008. Traumatic brain injury in burned service members: preliminary report. *J Trauma*. 64, S200-S206.
- Goossens, K.A., Maren, S., 2001. Contextual and auditory fear conditioning are mediated by the lateral, basal, and central amygdaloid nuclei in rats. *Learning & Memory*. 8, 148-155.
- Grillon, C., 2002. Startle reactivity and anxiety disorders; aversive conditioning, context, and neurobiology. *Biol Psychiatry*. 52, 958-975.
- Grillon, C., Morgan, C.A., 3<sup>rd</sup>, 1999. Fear-potentiated startle conditioning to explicit and contextual cues in Gulf War veterans with posttraumatic stress disorder. *J Abnormal Psychology*. 108, 134-142.
- Helmstetter, F.J., Parsons, R.G., Gafford, G.M., 2008. Macromolecular synthesis, distributed synaptic plasticity, and fear conditioning. *Neurobiology of Learning and Memory*. 89, 324-337.
- Henninger N., Dützmann, S., Sicard, K.M., Kollmar, R., Bardutzky, J., Schwab, S., 2005. Impaired spatial learning in a novel rat model of mild cerebral concussion injury. *Experimental Neurology*. 195, 447-457.
- Henninger, N., Sicard, K.M., Li, X., Kulkarni, P., Dützmann, S., Urbanek, C., Schwab, S., Fisher, M., 2007. Differential recovery of behavioral status and brain function assessed with functional magnetic resonance imaging after mild traumatic brain injury in the rat. *Crit Care Med*. 35, 2607-2614.
- Herman, J.P., Ostrander, M.M., Mueller, N.K., Figueiredo, H., 2005. Limbic system mechanisms of stress regulation: hypothalamo-pituitary-adrenocortical axis. *Prog Neuropsychopharmacol Biol Psychiatry*. 29, 1201-1213.
- Hoge, C.W., McGurk, D., Thomas, J.L., Cox, A.L., Engel, C.C., Castro, C.A., 2008. Mild traumatic brain injury in U.S. soldiers returning from Iraq. *N Engl J Med*. 358, 453-463.
- Hopper, J.W., Frewen, P.A., van der Kolk, B.A., Lanius, R.A., 2007. Neural correlates of re-experiencing, avoidance and dissociation in PTSD: symptoms dimensions and emotion dysregulation in responses to script-driven trauma imagery. *J Traumatic Stress*. 20, 713-725.
- Hunsaker, M.R., Kesner, R.P., 2008. Dissociation across the dorsal-ventral axis of CA3 and CA1 for encoding and retrieval of contextual and auditory-cued fear. *Neurobiol Learn Mem*. 89, 61-69.
- Kennedy, J.E., Jaffee, M.S., Leskin, G.A., Stokes, J.W., Leal, F.O., Fitzpatrick, P.J., 2007. Posttraumatic stress disorder and posttraumatic stress disorder-like symptoms and mild traumatic brain injury. *JJRD*. 44, 895-920.
- Kreisman, N.R., Soliman, S., Gozal, D., 2000. Regional differences in hypoxic depolarization and swelling in hippocampal slices. *J Neurophysiology*. 83, 1031-1038.
- Kwon, S-KC., Kovesdi, E., Gyorgy, A.B., Wingo, D., Kamnaksh, A., Walker, J., Long, J.B., Agoston, D.V., 2011. Stress and traumatic brain injury; a behavioral, proteomics and histological study. *Frontiers in Neurology*, 2, 1-13.

- Lewine, J.D., Davis, J.T., Bigler, E.D., Thoma, R., Hill, D., Funke, M., Sloan, J.H., Hall, S., Orrison, W.W., 2007. Objective documentation of traumatic brain injury subsequent to mild head trauma: Multimodal brain imaging with MEG, SPECT, and MRI. *J Head Trauma Rehabil.* 22, 141-155.
- Liberzon, I., Taylor, S.F., Amdur, R., Jung, T.D., Chamberlain, K.R., Minoshima, S., Koeppe, R.A., Fig, L.M., 1999. Brain activation in PTSD in response to trauma-related stimuli. *Biol Psychiatry.* 45, 817-826.
- Lukkes, J.L., Mokin, M.V., Scholl, J.L., Forster, G.L., 2009. Adult rats exposed to early-life social isolation exhibit increased anxiety and conditioned fear behavior, and altered hormonal stress responses. *Hormones and Behavior.* 55, 248-256.
- Madathil, S.K., Evans, H.N., Saatman, K.E., 2010. Temporal and regional changes in IGF-1/IGF-1R signaling in the mouse brain after traumatic brain injury. *J. Neurotrauma.* 27, 95-107.
- Malherbe, P., Borroni, E., Gobbi, L., Knust, H., Nettekoven, M., Pinard, E., Roche, O., Rogers-Evans, M., Wettstein, J.G., Moreau, J.L., 2009. Biochemical and behavioural characterization of EMPA, a novel high-affinity, selective antagonist for the OX<sub>2</sub> receptor. *British Journal of Pharmacology.* 156, 1326-1341.
- McNaughton, N., Corr, P.J., 2004. A two-dimensional neuropsychology of defense: fear/anxiety and defensive distance. *Neuroscience & Biobehavioral Reviews.* 28, 285-305.
- Milad, M.R., Orr, S.P., Lasko, N.B., Chang, Y., Rauch, S.L., Pitman, R.K., 2008. Presence and acquired origin of reduced recall for fear extinction in PTSD: results of a twin study. *Journal of Psychiatric Research.* 42, 515-520.
- Milad, M.R., Rauch, S.L., Pitman, R.K., Quirk, G.J., 2006. Fear extinction in rats: Implications for human brain imaging and anxiety disorders. *Biological Psychology.* 73, 61-71.
- Moore, E.L., Terryberry-Spohr, L., Hope, D.A., 2006. Mild traumatic brain injury and anxiety sequelae: A review of the literature. *Brain Injury.* 20, 117-132.
- Morales, D.M., Marklund, N., Lebold, D., Thompson, H.J., Pitkanen, A., Maxwell, W.L., Longhi, L., Laurer, H., Maegele, M., Neugebauer, E., Graham, D.I., Stocchetti, N., McIntosh, T.K., 2005. Experimental models of traumatic brain injury: Do we really need to build a better mousetrap?. *Neuroscience.* 136, 971-989.
- Mullen, R.J., Buck, C.R., Smith, A.M., 1992. NeuN, a neuronal specific nuclear protein in vertebrates. *Development.* 116, 201-211.
- Noshita, N., Lewen, A., Sugawara, T., Chan, P.H., 2002. Akt phosphorylation and neuronal survival after traumatic brain injury in mice. *Neurobiol. Dis.* 9, 294-304.
- Ooba, S., Hasuo, H., Shigemori, M., Yamashita, S., Akasu, T., 2009. Mild hypothermia prevents post-traumatic hyperactivity of excitatory synapses in rat hippocampal CA1 pyramidal neurons. *Kurume Med. J.* 56, 49-59.
- Paxinos, C., Watson, C., 1997. *The Rat Brain in Stereotaxic Coordinates*, 3rd ed. Academic Press, New York.
- Ptito, A., Chen, J.K., Johnston, K.M., 2007. Contributions of functional magnetic resonance imaging (fMRI) to sport concussion evaluation. *NeuroRehabilitation.* 22, 217-227.
- Quirk, G.J., Garcia, R., Gonzalez-Lima, F., 2006. Prefrontal mechanisms in extinction of conditioned fear. *Biol Psychiatry.* 60, 337-343.
- Quirk, G.J., Likhtik, E., Pelletier, J.G., Paré D., 2003. Stimulation of medial prefrontal cortex decreases the responsiveness of central amygdala output neurons. *J Neurosci.* 23, 8800-8807.
- Rauch, S.L., Shin, L.M., Phelps, E.A., 2006. Neurocircuitry models of posttraumatic stress disorder and extinction: Human neuroimaging research—Past, present, and future. *Biol Psychiatry.* 60, 376-382.
- Rauch, S.L., Whalen, P.J., Shin, L.M., McInerney, S.C., Macklin, M.L., Lasko, N.B., Orr, S.P., Pitman, R.K., 2000. Exaggerated amygdala response to masked facial stimuli in posttraumatic stress disorder: A functional MRI study. *Biol Psychiatry.* 47, 769-776.
- Rubovich, V., Edut, S., Sarfstein, R., Werner, H., Pick, C.G. 2010. The intricate involvement of the insulin-like growth factor receptor signaling in mild traumatic brain injury in mice. *Neurobiol. Dis.* 38, 299-303.

- Schienle, A., Ebner, F., Schäfer, A., 2011. Localized gray matter volume abnormalities in generalized anxiety disorder. *European Archives of Psychiatry and Clinical Neuroscience*. 261, 303-307.
- Schmidt-Kastner, R., Freund, T.F., 1991. Selective vulnerability of the hippocampus in brain ischemia. *Neuroscience*. 40, 599-636.
- Shapira, M., Licht, A., Milman, A., Picj, C.G., Shohami, E., Elder-Finkelman, H., 2007. Role of glycogen synthase kinase-3B in early depressive behavior induced by mild traumatic brain injury. *Mol. Cell. Neurosci*. 34, 571-577.
- Shin, L.M., Wright, C.I., Cannistraro, P.A., Wedig, M.M., McMullin, K., Martis, B., Macklin, M.L., Lasko, N.B., Cavanagh, S.R., Krangel, T.S., Orr, S.P., Pitman, R.K., Whalen, P.J., Rauch, S.L., 2005. A functional magnetic resonance imaging study of amygdala and medial prefrontal cortex responses to overtly presented fearful faces in posttraumatic stress disorder. *Arch Gen Psychiatry*. 62, 273-281.
- Shin, L.M., Orr, S.P., Carson, M.A., Rauch, S.L., Macklin, M.L., Lasko, N.B., Peters, P.M., Metzger, L.J., Daugherty, D.D., Cannistraro, P.A., Alpert, N.M., Fischman, A.J., Pitman, R.K., 2004. Regional cerebral blood flow in the amygdala and medial prefrontal cortex during traumatic imagery in male and female Vietnam veterans with PTSD. *Arch Gen Psychiatry*. 61, 168-176.
- Shin, L.M., Whalen, P.J., Pitman, R.K., Bush G., Macklin, M.L., Lasko, N.B., Orr, S.P., McInerney, S.C., Rauch, S.L., 2001. An fMRI study of anterior cingulate function in posttraumatic stress disorder. *Biol Psychiatry*. 50, 932-942.
- Slomianka, L., West, M.J., 2005. Estimators of the precision of stereological estimates: an example bases on the CA1 pyramidal cell layers of rats. *Neuroscience*. 136, 757-767.
- Sun, D., McGinn, M.J., Zhou, Z., Harvey, H.B., Bullock, M.R., Colello, R.J., 2007. Anatomical integration of newly generated dentate granule neurons following traumatic brain injury in adult rats and its association to cognitive recovery. *Exp Neurology* 204, 264-272.
- Tang, Y.P., Noda, Y., Hasegawa, T., Nabeshima, T., 1997a. A concussive-like brain injury model in mice (I): impairment in learning and memory. *J Neurotrauma*. 14, 851-862.
- Tang, Y.P., Noda, Y., Hasegawa, T., Nabeshima, T., 1997b. A concussive-like brain injury model in mice (II): selective neuronal loss in the cortex and hippocampus. *J Neurotrauma*. 14, 863-873.
- Tashlykov, V., Katz, Y., Gazit, V., Zohar, O., Schreiber, S., Pick, C.G., 2007. Apoptotic changes in the cortex and hippocampus following minimal brain trauma in mice. *Brain Research*. 1130, 197-205.
- Tashlykov, V., Katz, Y., Volkov, A., Gazit, V., Schreiber, S., Zohar, O., Pick, C., 2009. Minimal traumatic brain injury induce apoptotic cell death in mice. *J Molecular Neuroscience*. 37, 16-24.
- Tweedie, D., Milman, A., Holloway, H.W., Li, Y., Harvey, B.K., Shen, H., Pistell, P.J., Lahiri, D.K., Hoffer, B.J., Wang, Y., Pick, C.G., Greig, N.H., 2007. Apoptotic and behavioral sequelae of mild brain trauma in mice. *Journal of Neuroscience Research*. 85, 805-815.
- Vuong, S.M., Oliver, H.A., Scholl, J.L., Oliver, K.M., Forster, G.L., 2010. Increased anxiety-like behavior of rats during amphetamine withdrawal is reversed by CRF2 receptor antagonism. *Behav Brain Res*. 208, 278-281.
- Wallesch, C.W., Curio, N., Galazky, I., Jost, S., Synowitz, H., 2001. The neuropsychology of blunt head injury in the early postacute stage: Effects of focal lesions and diffuse axonal injury. *J Neruotrauma*. 18, 11-20.
- West, M.J., 1993. New Stereological methods for counting neurons. *Neurobiol Aging*. 14, 275-285.
- Yoshino, A., Hovda, D.A., Katayama, Y., Kawamata, T., Becker, D.P., 1996. Hippocampal CA3 lesion prevents postconcussive metabolic dysfunction in CA1. *J Cereb Blood Flow Metab*. 12, 996-1006.
- Zhang, X., Chen, Y., Ikonovic, M.D., Nathaniel, P.D., Kochanek, P.M., Marion, D.W., DeKosky, S.T., Jenkins, L.W., Clark, R.S., 2006. Increased phosphorylation of protein kinase B and related substrates after traumatic brain injury in humans and rats. *J. Cereb. Blood Flow Metab*. 26, 915-926.



## Figure Legends

### Figure 1

Total number of neurons in the amygdala subregions as measured at (**A, C, E**) 4 days and (**B, D, F**) 9 days following mTBI or control surgery. \* $P < 0.05$  compared to control group at the same time point. LA/BLA = lateral and basolateral amygdala; MeA = medial amygdala; CeA = central nucleus of the amygdala.

### Figure 2

Total number of neurons in the dorsal hippocampal subregions as measured at (**A, C, E**) 4 days and (**B, D, F**) 9 days following mTBI or control surgery. \* $P < 0.05$  compared to control group at the same time point. DG = dentate gyrus.

### Figure 3

Density of apoptotic cells in the amygdala subregions as measured at (**A, C, E**) 4 days and (**B, D, F**) 9 days following mTBI or control surgery. \* $P < 0.05$  compared to control group at the same time point. LA/BLA = lateral and basolateral amygdala; MeA = medial amygdala; CeA = central nucleus of the amygdala.

### Figure 4

Density of apoptotic cells in the dorsal hippocampus subregions as measured at (**A, C, E**) 4 days and (**B, D, F**) 9 days following mTBI or control surgery. \* $P < 0.05$  compared to control group at the same time point.

### Figure 5

(**A**) Level of freezing behavior in response to foot shock 8 days following mTBI or control surgery. (**B**) Time spent freezing in the context associated with foot shock on days 9-11 following mTBI or control surgery. (**C**) Latency to withdrawal tail in a thermal nociception test 12 days following mTBI or control surgery. \* $P < 0.05$  compared to control group on the same test day. <sup>#</sup> $P < 0.05$  compared to conditioning test day within the same treatment group.

## **Figure 6**

(**A**) Latency to enter open arms, (**B**) time spent in open arms and (**C**) total distance moved within the entire elevated plus maze, 6 days following mTBI or control surgery. \* $P < 0.05$  compared to control group.

## **Figure 7**

(**A**) Total distance moved within the foot shock chamber over 30 minutes in the absence of foot shock, 7 days following mTBI or control surgery. (**B**) Time spent on the rotarod during the 2 minute test, 10 days following mTBI or control surgery.

*Table 1: Physiological Parameters following mTBI or Sham Procedures*

Time (min)	O <sub>2</sub> Saturation (%)		Heart Rate (beats/min)		Breath Rate (breaths/min)	
	Control	mTBI	Control	mTBI	Control	mTBI
-1	98.82 ± 0.08	97.71 ± 0.79	301.61 ± 7.01	306.00 ± 4.80	42.69 ± 1.58	42.49 ± 1.69
0	98.22 ± 0.31	98.09 ± 0.36	299.63 ± 6.76	301.25 ± 4.92	40.28 ± 1.38	45.44 ± 2.59
2	96.75 ± 0.98	98.65 ± 0.09	304.55 ± 10.91	298.85 ± 16.33	44.34 ± 3.67	41.49 ± 2.54
4	96.94 ± 0.88 <sup>#</sup>	95.87 ± 0.77	297.18 ± 8.14	286.19 ± 7.56	40.55 ± 2.77	48.08 ± 6.35
6	96.00 ± 0.81 <sup>#</sup>	94.61 ± 0.86 <sup>#</sup>	306.66 ± 12.78	290.82 ± 5.64	46.47 ± 3.48	62.99 ± 2.97* <sup>#</sup>
8	95.08 ± 0.61 <sup>#</sup>	93.66 ± 1.54 <sup>#</sup>	300.93 ± 8.55	323.00 ± 16.32	58.32 ± 4.54 <sup>#</sup>	55.94 ± 4.90 <sup>#</sup>

Note that isoflurane/O<sub>2</sub> was removed by 6 min post-mTBI or sham procedures.

\* Significantly different from control within same time period (P < 0.05)

<sup>#</sup> Significantly different compared to -1 min (P < 0.05)

Table 2: Area (mm<sup>2</sup>) of Specific Limbic Regions following mTBI

Brain Region	4 Days Post-Procedure			9 Days Post-Procedure		
	Control	mTBI	P Value	Control	Day mTBI	P Value
<i>Medial Prefrontal Cortex</i>						
Cg	362.72 ± 67.57	280.32 ± 33.22	0.276	350.47 ± 45.46	345.60 ± 40.16	0.937
PrL	166.75 ± 28.11	118.56 ± 4.23	0.159	44.50 ± 7.61	60.62 ± 11.69	0.271
IL	65.16 ± 14.36	50.21 ± 1.39	0.289	135.57 ± 25.82	157.30 ± 31.08	0.600
<i>Amygdala</i>						
CeA	30.80 ± 8.46	31.80 ± 5.67	0.967	44.25 ± 10.44	34.32 ± 8.21	0.481
BLA/LA	85.07 ± 21.63	72.86 ± 16.94	0.689	121.38 ± 4.07	232.32 ± 34.27	0.026
MeA	54.21 ± 17.20	82.72 ± 18.59	0.293	132.35 ± 9.24	234.78 ± 29.77	0.023
<i>Cortex</i>	1323.52 ± 300.04	1650.88 ± 149.66	0.329	1732.94 ± 125.02	1555.48 ± 54.86	0.270
<i>Dorsal Hippocampus</i>						
CA1	674.93 ± 114.65	640.36 ± 76.03	0.806	613.82 ± 50.30	493.50 ± 18.39	0.059
CA3	334.32 ± 52.84	329.21 ± 35.47	0.937	291.43 ± 22.25	283.36 ± 17.98	0.783
DG	238.86 ± 32.34	224.27 ± 22.32	0.717	185.33 ± 12.73	166.09 ± 10.55	0.267
<i>Ventral Hippocampus</i>						
CA1	100.32 ± 28.61	124.96 ± 11.91	0.450	57.29 ± 10.73	60.50 ± 9.00	0.822
CA3	142.56 ± 67.62	95.74 ± 27.89	0.478	40.46 ± 7.63	38.50 ± 5.27	0.842
DG	163.33 ± 25.80	172.73 ± 16.70	0.755	38.50 ± 6.38	60.89 ± 8.52	0.057

Cg = cingulate, PrL = prelimbic, IL = infralimbic, CeA = central nucleus, BLA/LA = basolateral and lateral, MeA = medial amygdala, DG = dentate gyrus.

Table 3: Total Number of Neurons in Specific Limbic Regions following mTBI

	4 Days Post-Procedure			9 Days Post-Procedure		
	Control	mTBI	P Value	Control	mTBI	P Value
<i>Medial Prefrontal Cortex</i>						
CG	92160.71 ± 19337.02	78273.66 ± 9049.29	0.530	99286.45 ± 12181.15	98137.30 ± 10002.69	0.943
PrL	30545.07 ± 1175.28	44221.40 ± 7857.68	0.281	39253.33 ± 7553.60	46815.70 ± 9037.28	0.533
IL	44221.44 ± 7857.68	30545.07 ± 1175.28	0.281	12993.42 ± 2507.67	17323.28 ± 3348.31	0.336
<i>Cortex</i>	466522.09 ± 127608.45	561369.60 ± 58655.45	0.469	583767.00 ± 36612.65	543781.38 ± 38842.96	0.509
<i>Ventral Hippocampus</i>						
CA1	36422.69 ± 13129.13	37690.43 ± 4965.53	0.930	11454.19 ± 2160.06	10717.12 ± 1699.00	0.794
CA3	55758.79 ± 28659.97	32277.61 ± 12468.29	0.413	12000.61 ± 2863.12	10081.61 ± 1814.10	0.598
DG	67507.34 ± 9429.59	72323.65 ± 9231.63	0.730	10463.84 ± 2202.31	15158.82 ± 1163.10	0.101

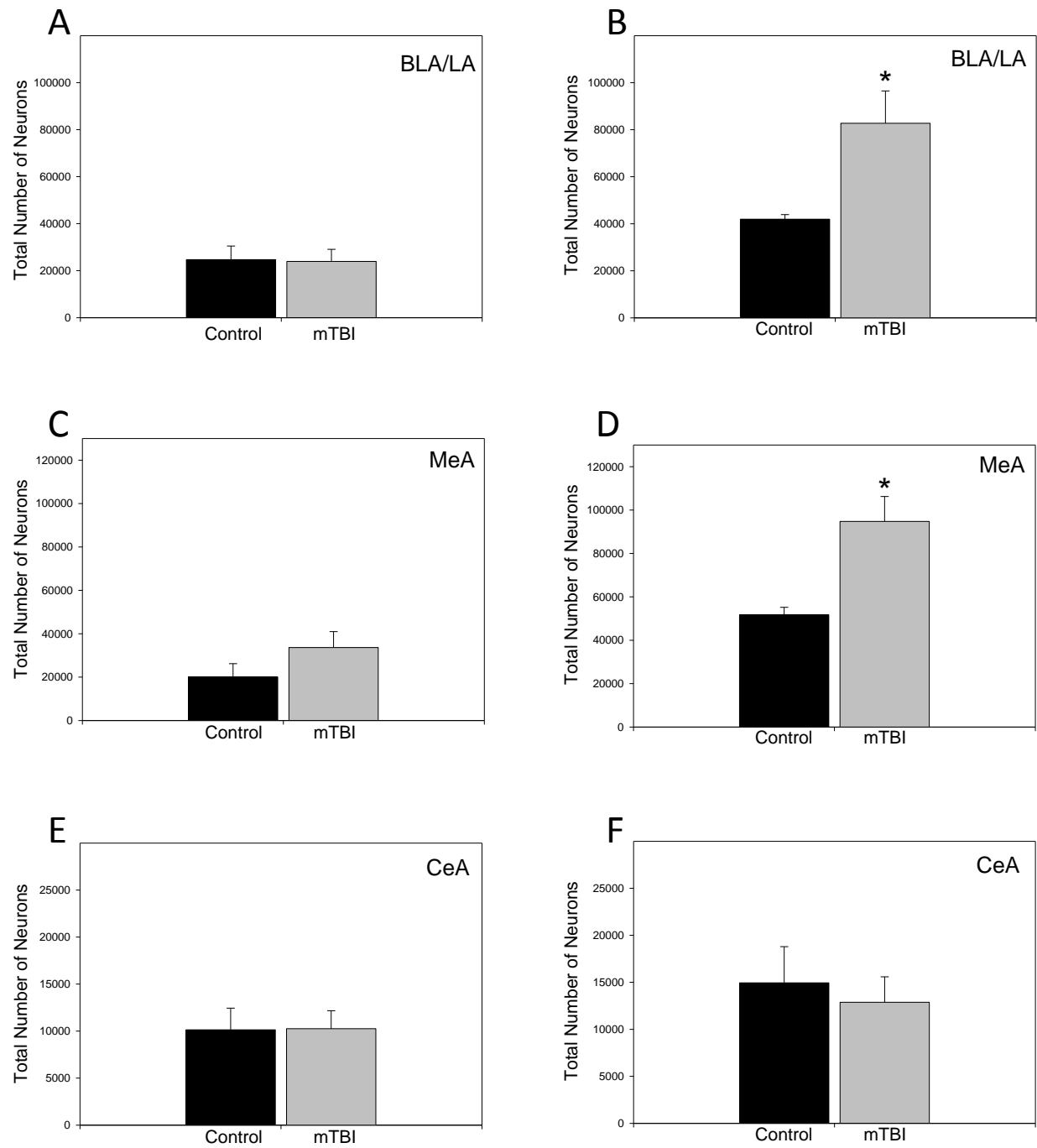
Cg = cingulate, PrL = prelimbic, IL = infralimbic, DG = dentate gyrus.

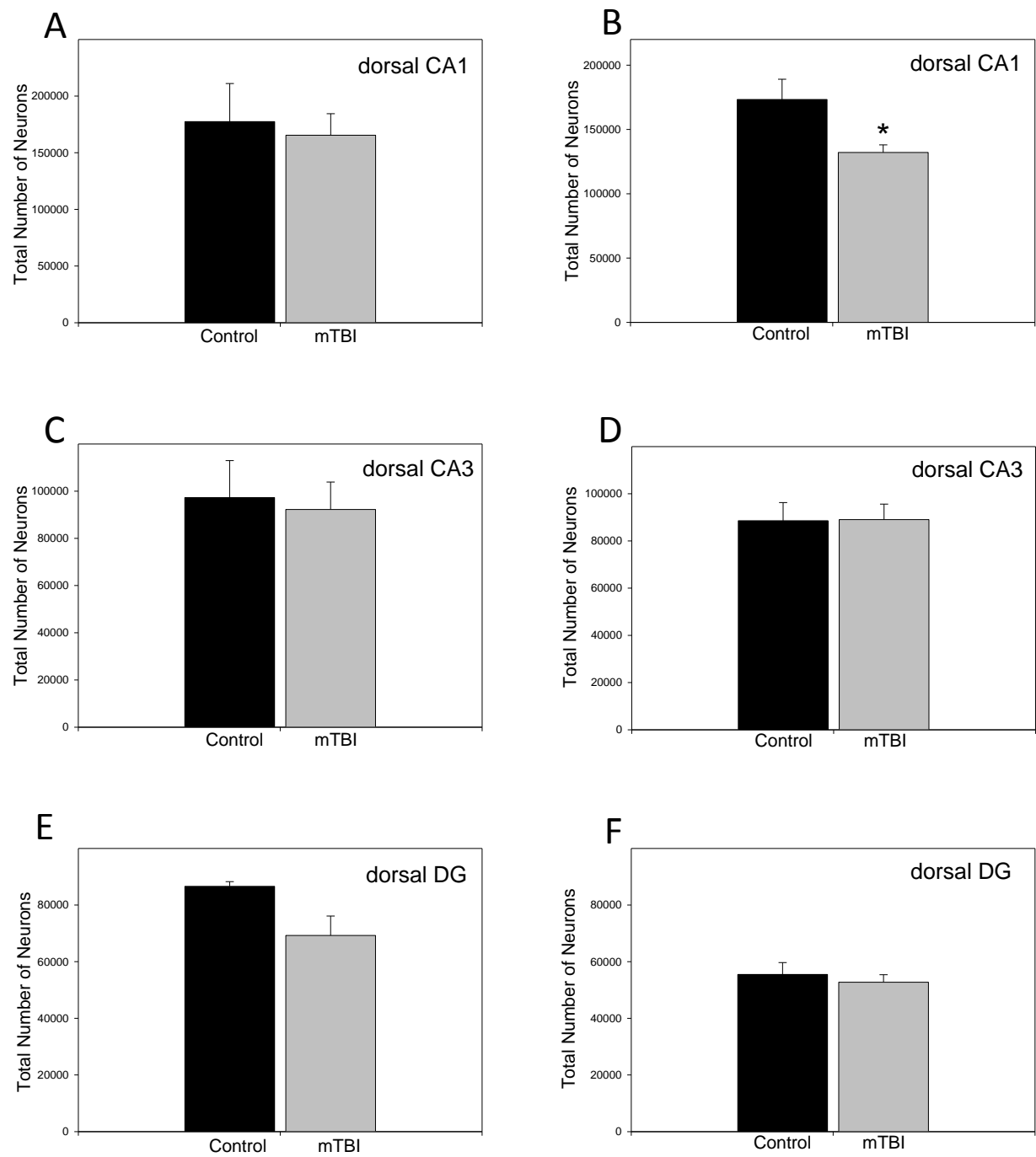
*Table 4: Density of TUNEL-Positive Cells (per mm<sup>2</sup>) in Specific Limbic Regions following mTBI*

	4 Days Post-Procedure			9 Days Post-Procedure		
	Control	mTBI	P Value	Control	mTBI	P Value
<i>Medial Prefrontal Cortex</i>						
CG	$1.98 \pm 0.31e^{-3}$	$2.41 \pm 0.40e^{-3}$	0.419	$2.48 \pm 0.68e^{-3}$	$1.75 \pm 0.27e^{-3}$	0.368
PrL	$2.10 \pm 0.40e^{-3}$	$2.02 \pm 0.25e^{-3}$	0.866	$1.92 \pm 0.40e^{-3}$	$1.90 \pm 0.58e^{-3}$	0.982
IL	$3.55 \pm 0.54e^{-3}$	$2.38 \pm 0.21e^{-3}$	0.068	$2.53 \pm 0.41e^{-3}$	$2.10 \pm 0.37e^{-3}$	0.459
<i>Cortex</i>						
	$1.89 \pm 0.32e^{-3}$	$2.16 \pm 0.64e^{-3}$	0.803	$1.57 \pm 0.36e^{-3}$	$2.21 \pm 0.62e^{-3}$	0.394
<i>Ventral Hippocampus</i>						
CA1	$1.33 \pm 0.17e^{-3}$	$1.68 \pm 0.22e^{-3}$	0.271	$3.71 \pm 0.92e^{-3}$	$1.98 \pm 0.47e^{-3}$	0.137
CA3	$2.08 \pm 0.82e^{-3}$	$2.72 \pm 0.94e^{-3}$	0.647	$2.88 \pm 0.84e^{-3}$	$2.15 \pm 0.47e^{-3}$	0.490
DG	$3.57 \pm 0.69e^{-3}$	$3.02 \pm 0.30e^{-3}$	0.513	$5.23 \pm 0.68e^{-3}$	$4.36 \pm 0.83e^{-3}$	0.437

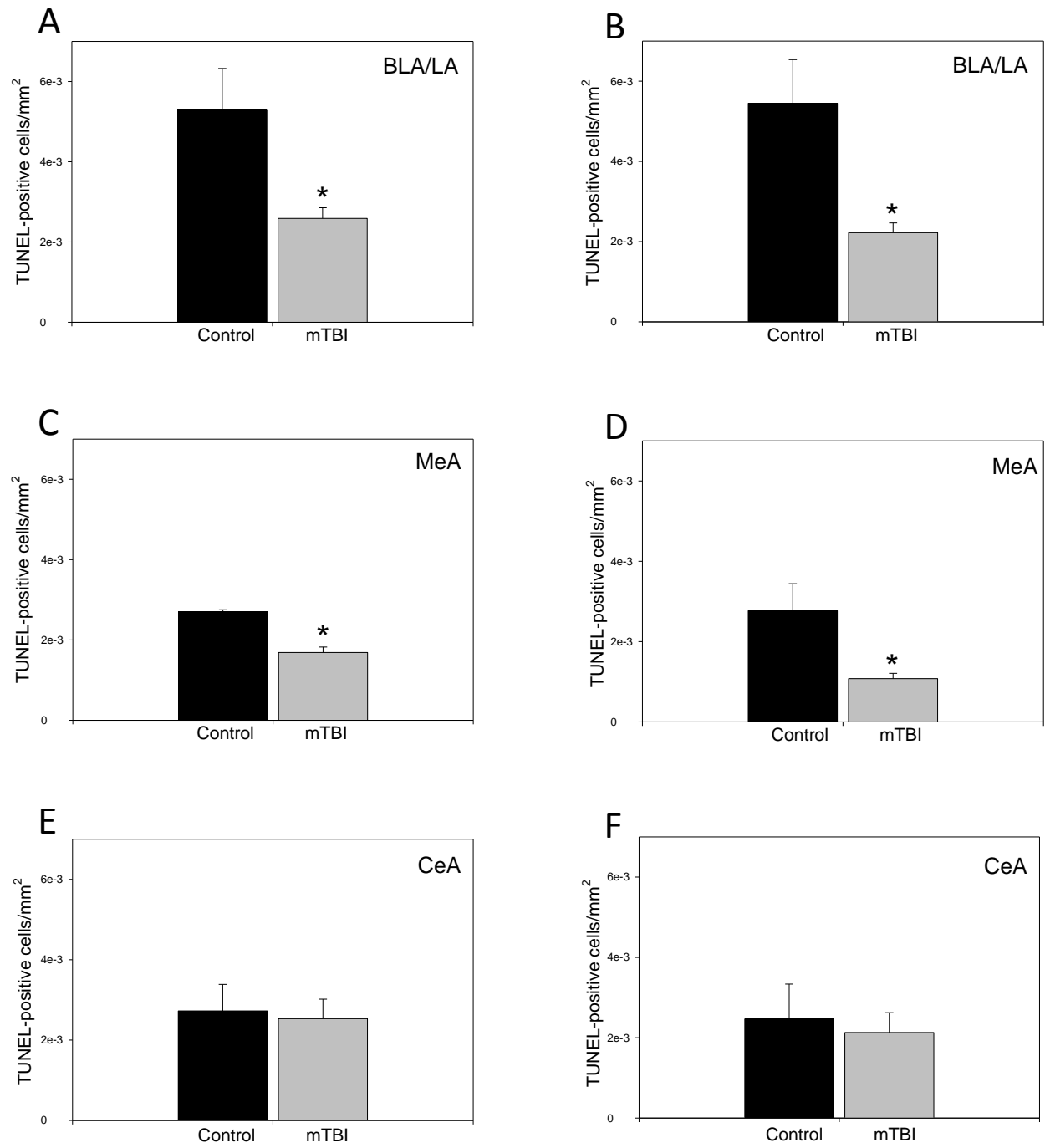
Cg = cingulate, PrL = prelimbic, IL = infralimbic, DG = dentate gyrus.

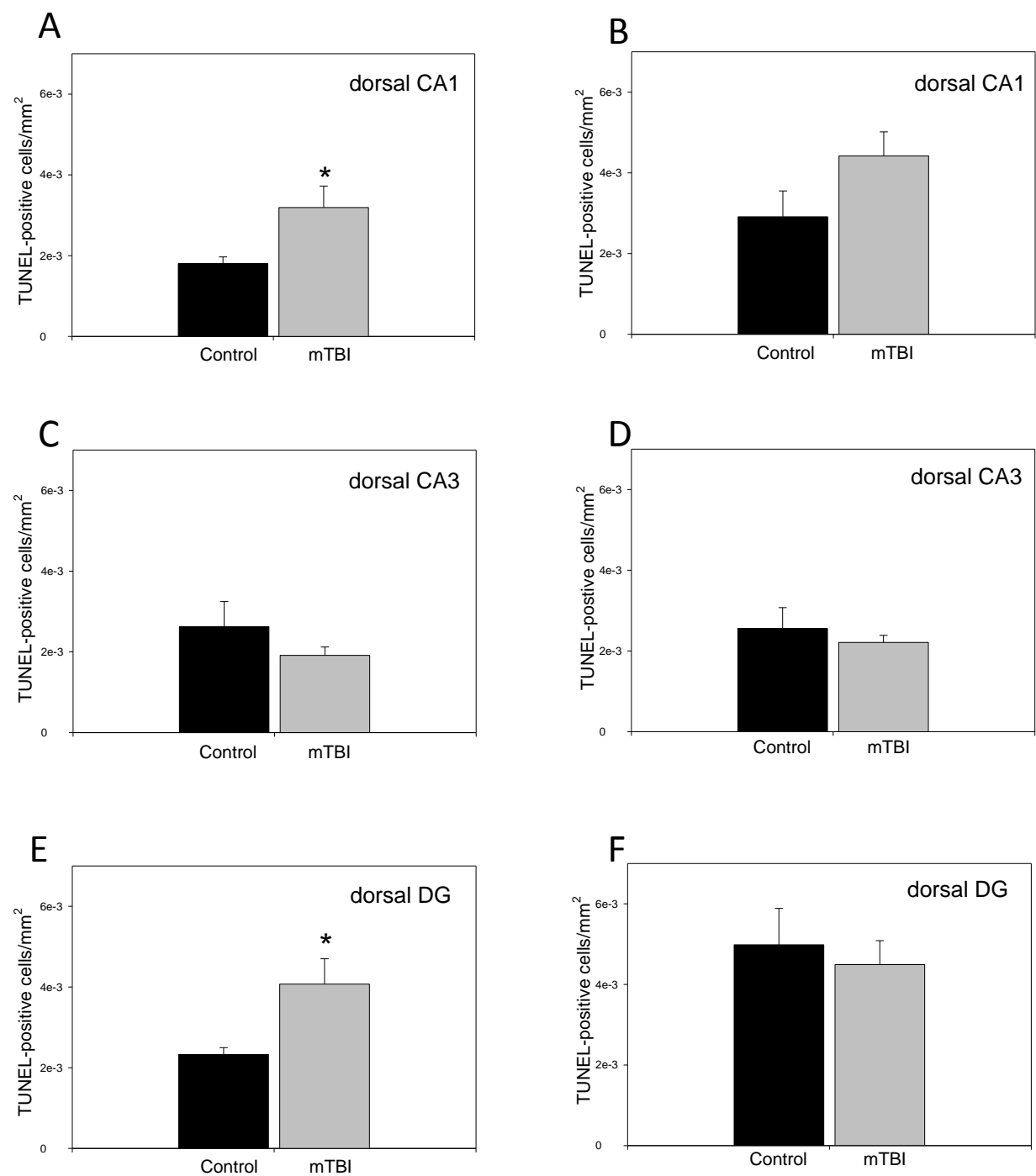
Meyer et al. Figure 1

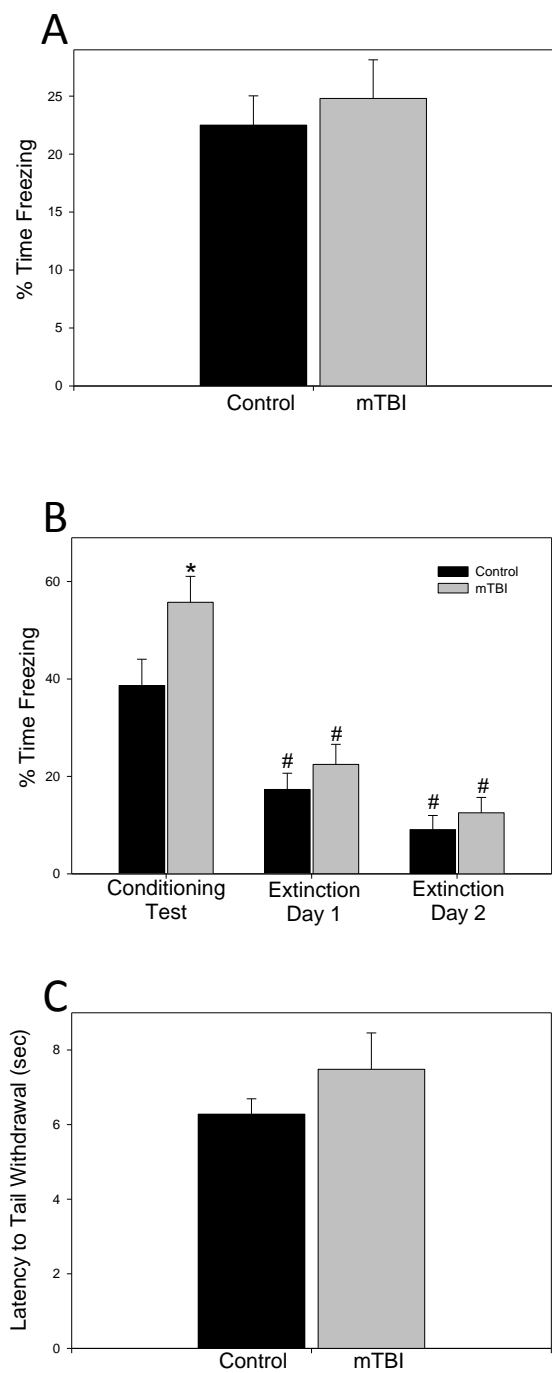


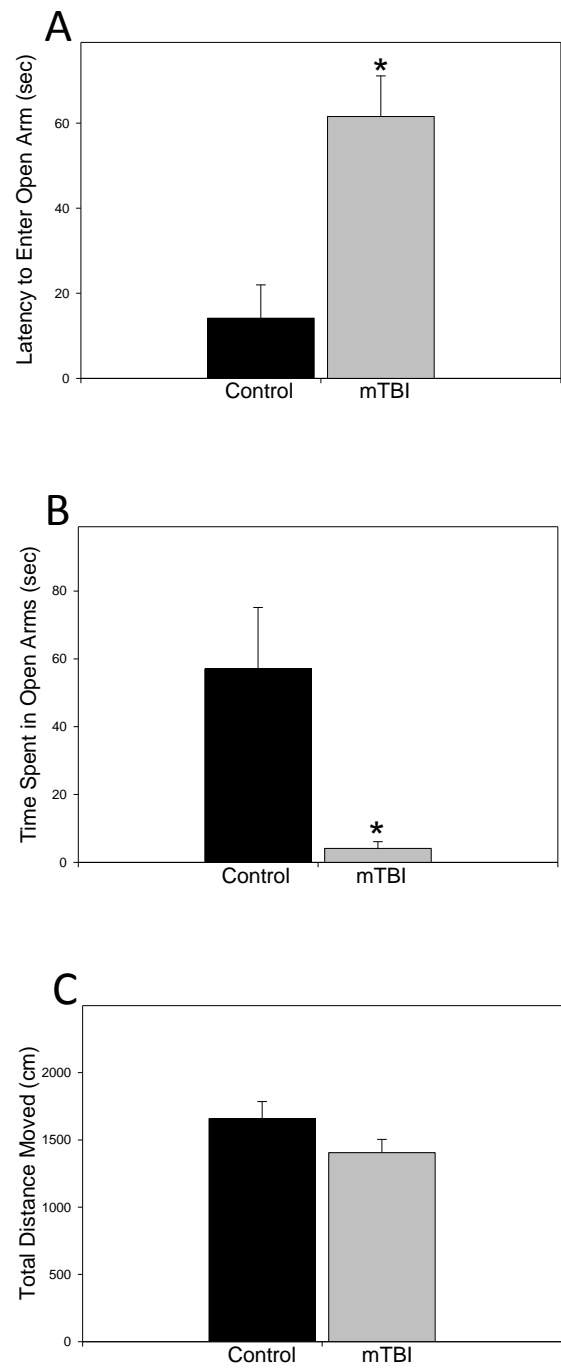












Meyer et al. Figure 7

